Pre-Main-Sequence Ages
Taurus and the Environmental Impact on Disc Lifetime

Jon Rees

School of Physics
University of Exeter

Tim Naylor, Cameron Bell, Tom Wilson,
Nathan Mayne, Darryl Sergison, Rob Jeffries

Background Image Credit: NASA, ESA, and G. Bacon (STScI)

CTIO/NOAO

6th August 2015

Overview

1) Introduction:

- Review work of collaborators
  - Age fitting techniques
  - The PMS age crisis
- Taurus

2) Extinction fitting

3) Application to Taurus, age fitting, implications

The Papers

Are pre-main-sequence stars older than we thought? – Naylor (2009)

Pre-main-sequence isochrones - I. The Pleiades benchmark – Bell, Mayne, Naylor, Jeffries & Littlefair (2012)

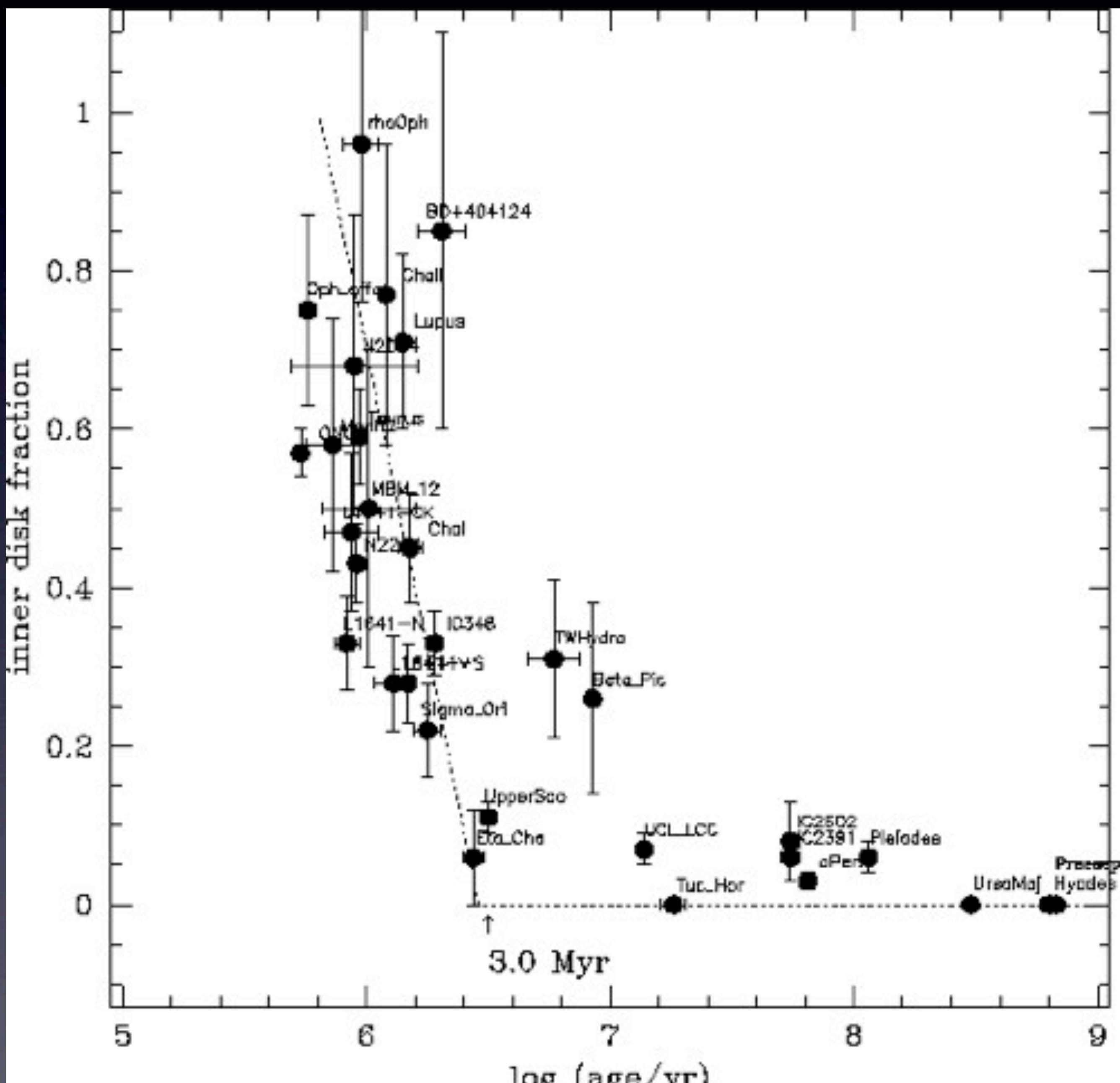
Pre-main-sequence isochrones – II. Revising star and planet formation timescales – Bell et al, MNRAS (2013)

Pre-main-sequence isochrones – III. The Cluster Collaboration isochrone server – Bell et al, MNRAS (2014)

Motivation I

- Why are we interested?
  - Stellar ages give us timescales
  - Disc lifetime, planet formation, YSO lifetimes
  - Star formation rates, masses

Motivation II: Planet formation



Credit: Lynn Hillenbrand

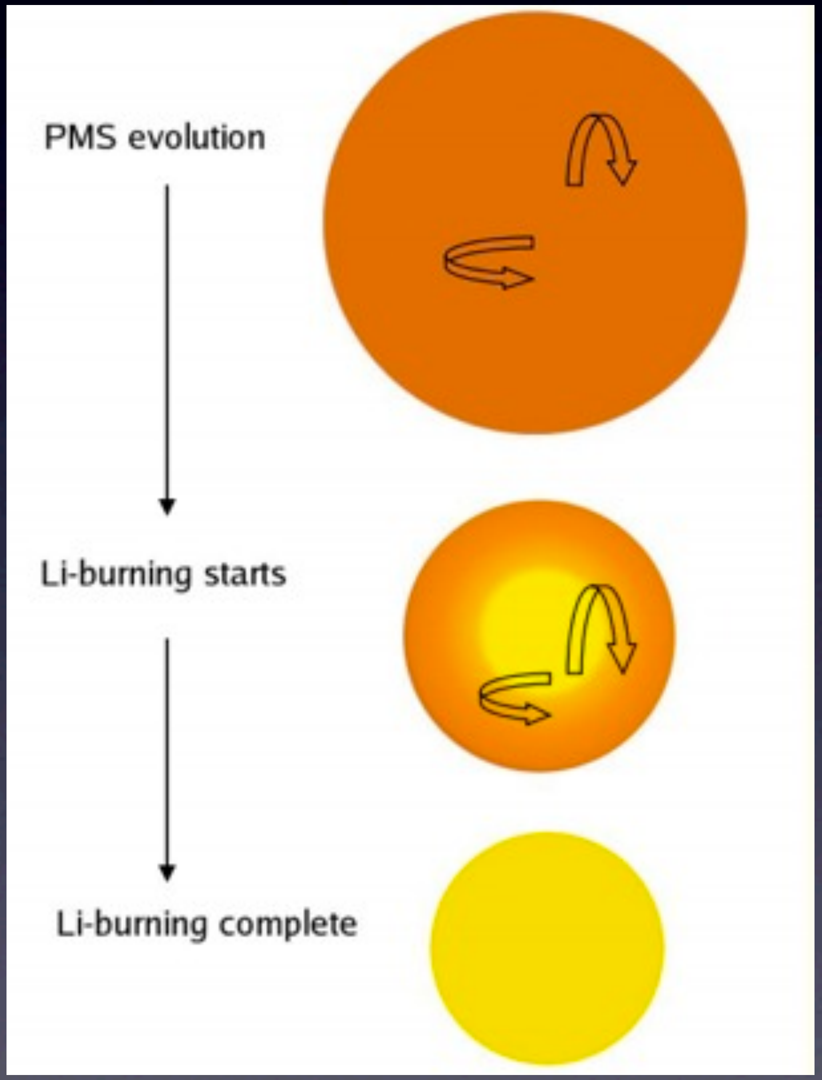
- IR excess (dust disc) disappears in ~2Myr.
- But takes ~10Myr to form Jupiter.
- Are planets rare?
- Is environment important?

The three ages of young stars

- Lithium depletion ages (only good for >15 Myr)
- Pre-main-sequence ages
- ZAMS to TAMS evolution (MS ages)

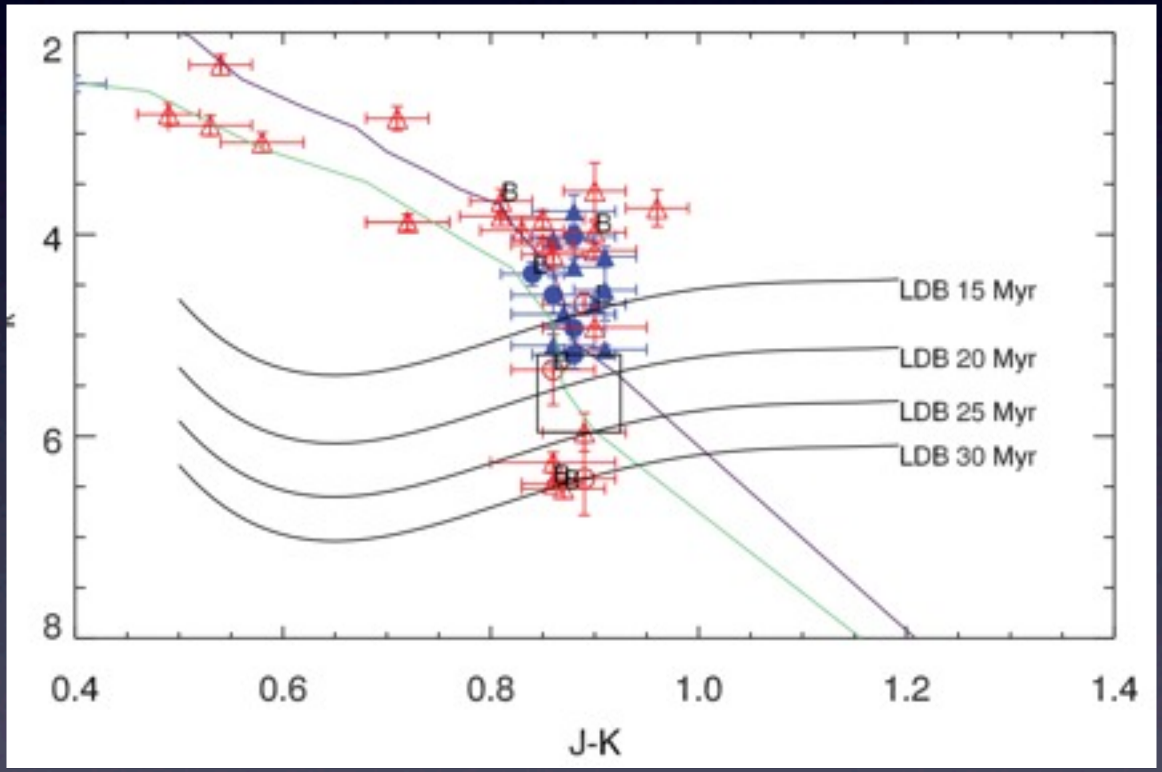
Lithium Depletion

- Li burned rapidly at $T_C=3x10^6K$
- Low mass PMS stars fully convective
- Lithium depleted throughout star



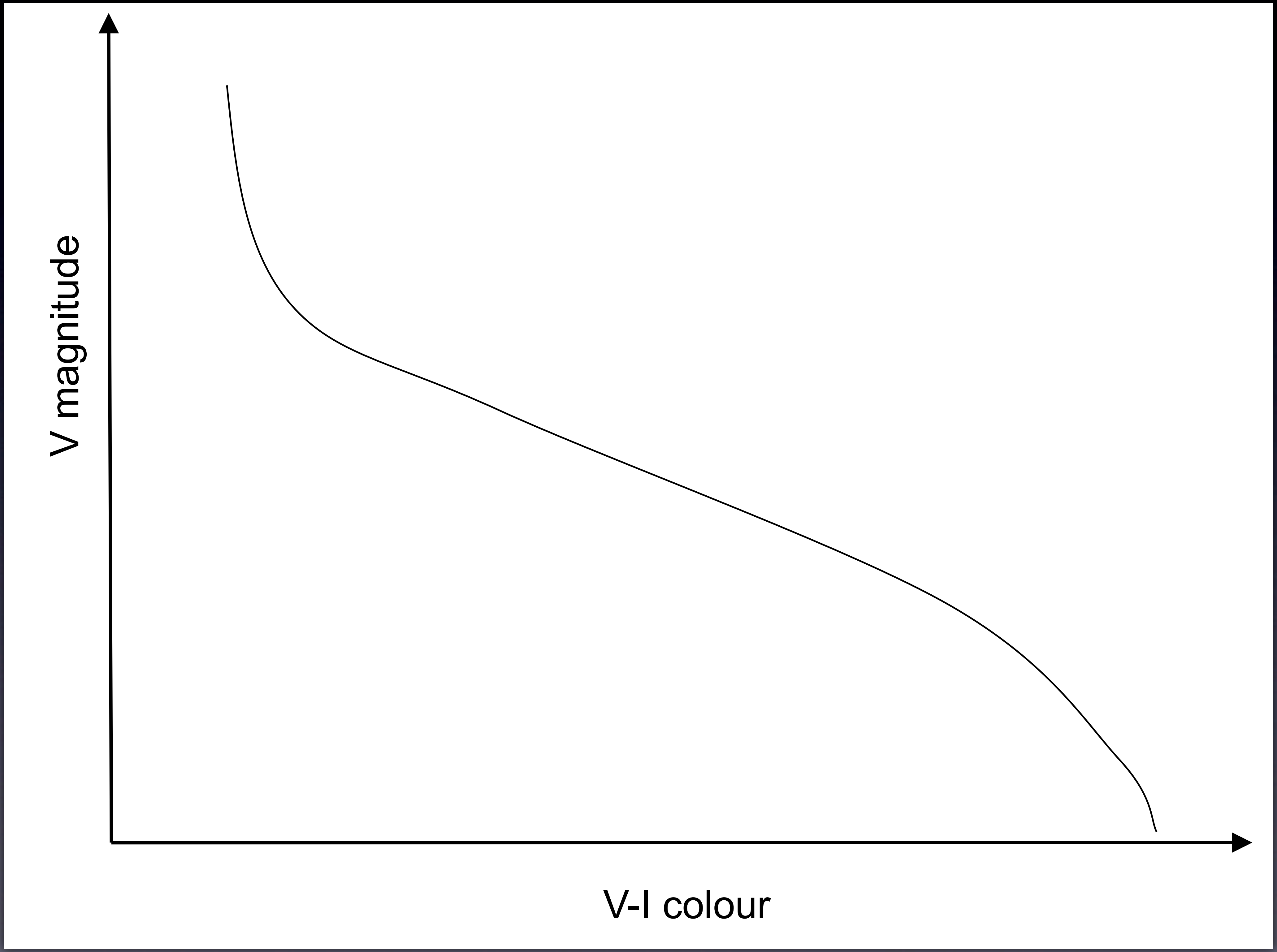
Lithium Depletion

- Age of lithium depletion is mass dependent
- Boundary between stars with lithium and depleted lithium
- Luminosity of boundary age is model independent
- 9 clusters: 22-132Myr

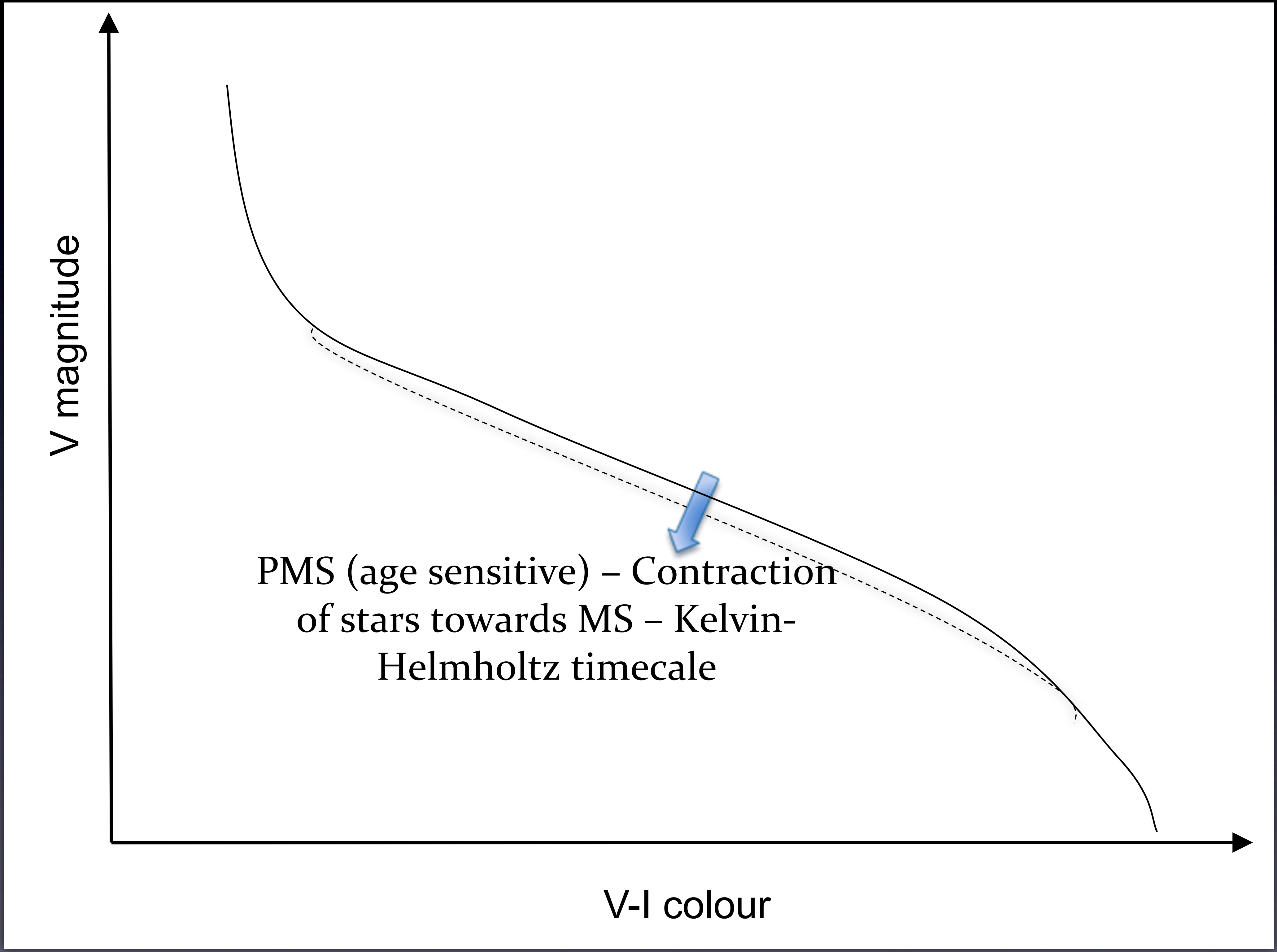


Binks & Jeffries (2014)

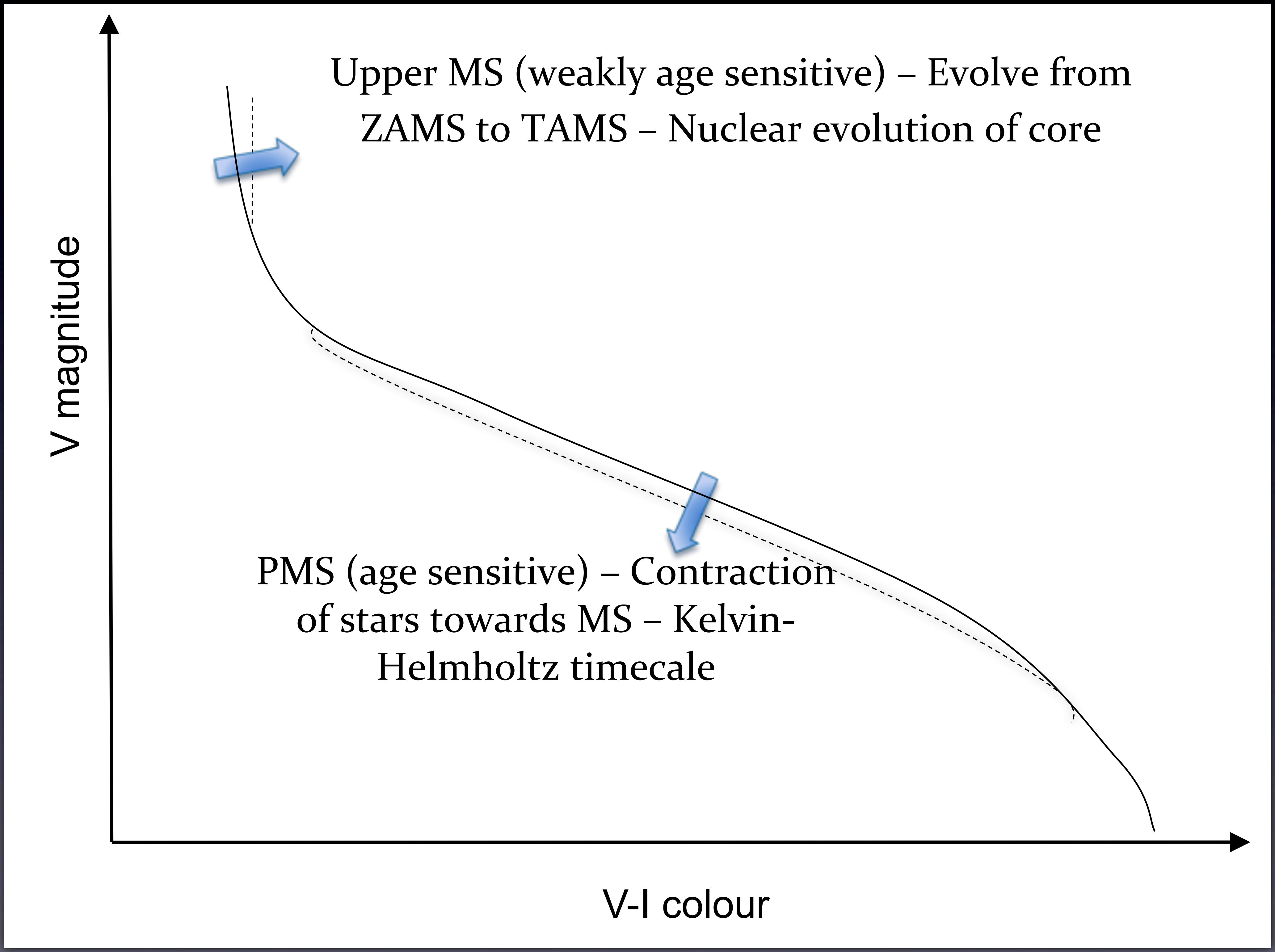
Ages from the CMD



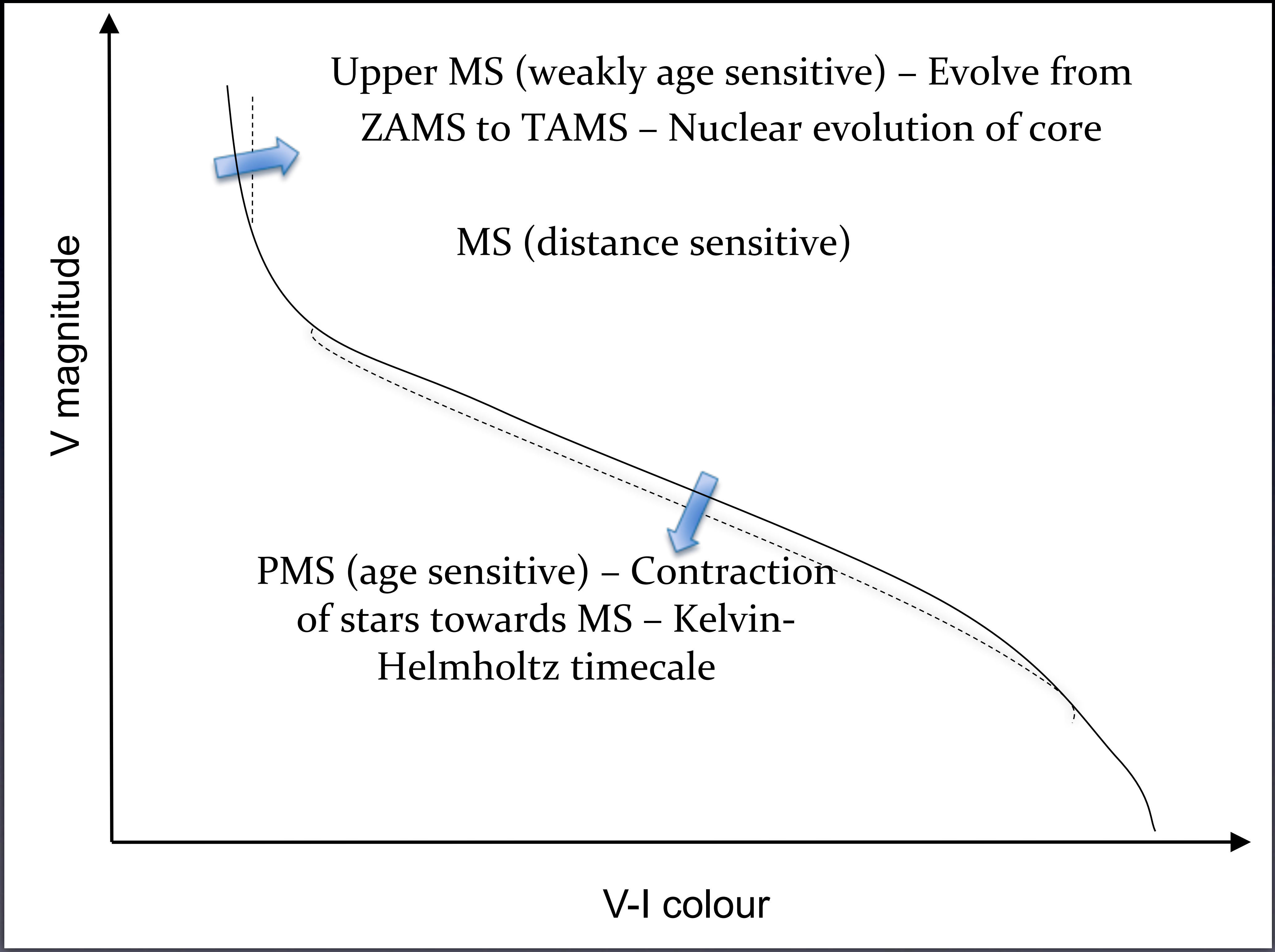
Ages from the CMD



Ages from the CMD



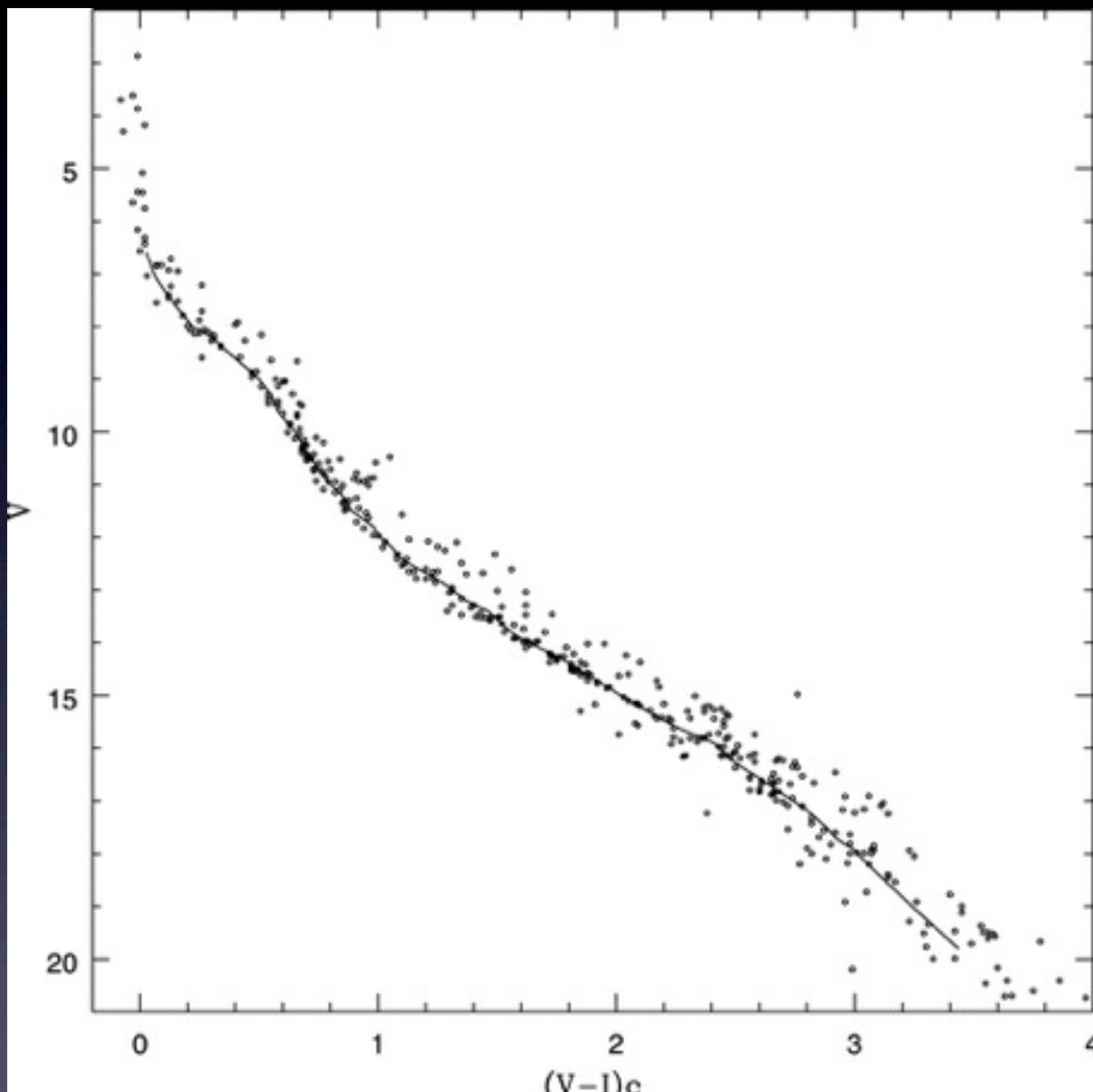
Ages from the CMD



Upper-Main-Sequence fitting

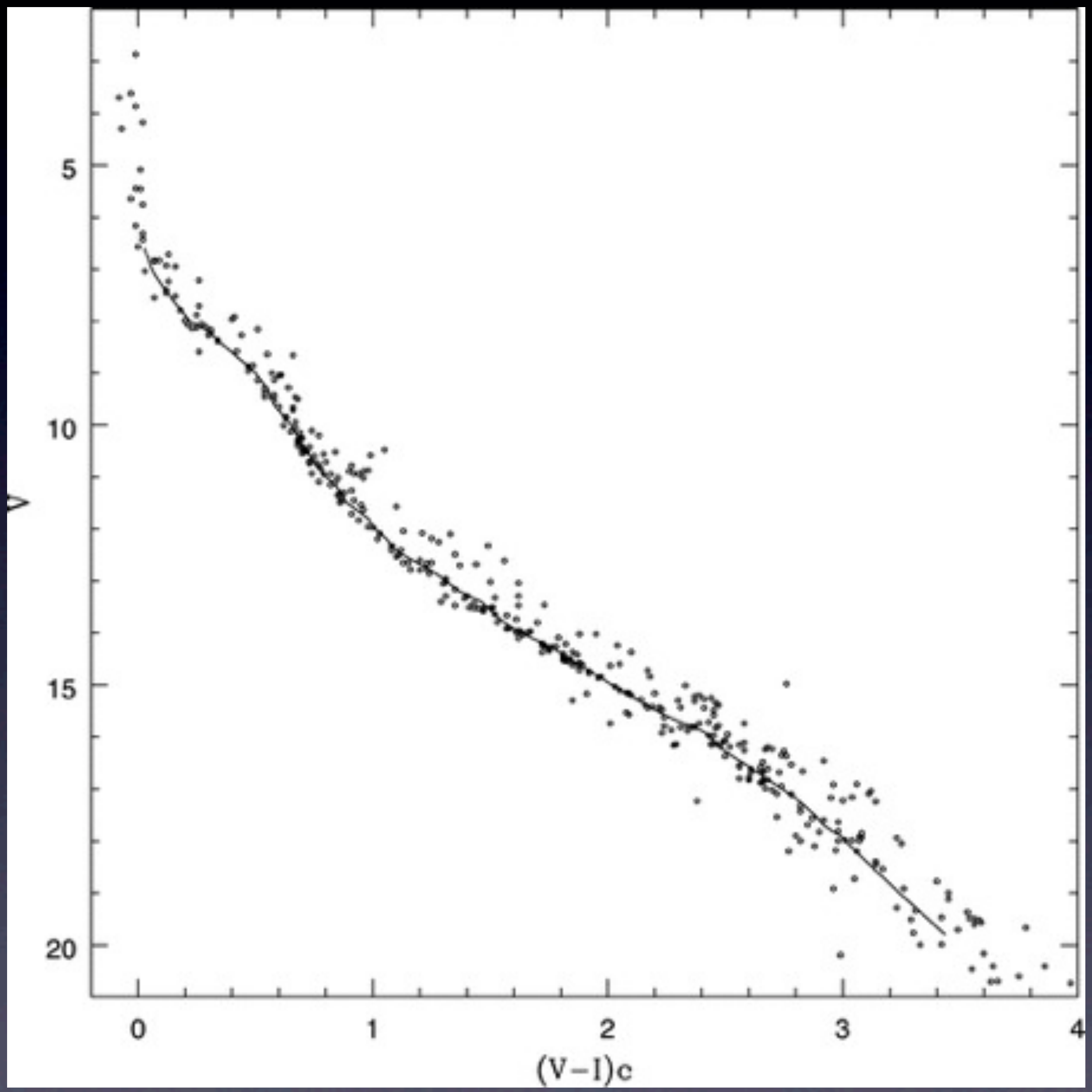
- Reminder – the UMS stars evolves from ZAMS to TAMS over ~10Myr.
- These stars are bright (V<10).
- Database of superb *UBV* photometry from Johnson and collaborators (1950s-1980s).
- Fit distance, age and extinction.

Fitting the CMD - The problem



V vs. $(V\text{-}I)_c$ CMD for Pleiades members with photoelectric photometry. The solid curve is the “by-eye” fit to the single-star locus for Pleiades members. (From Stauffer 2007.)

Fitting the CMD - The problem



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Why not χ^2?

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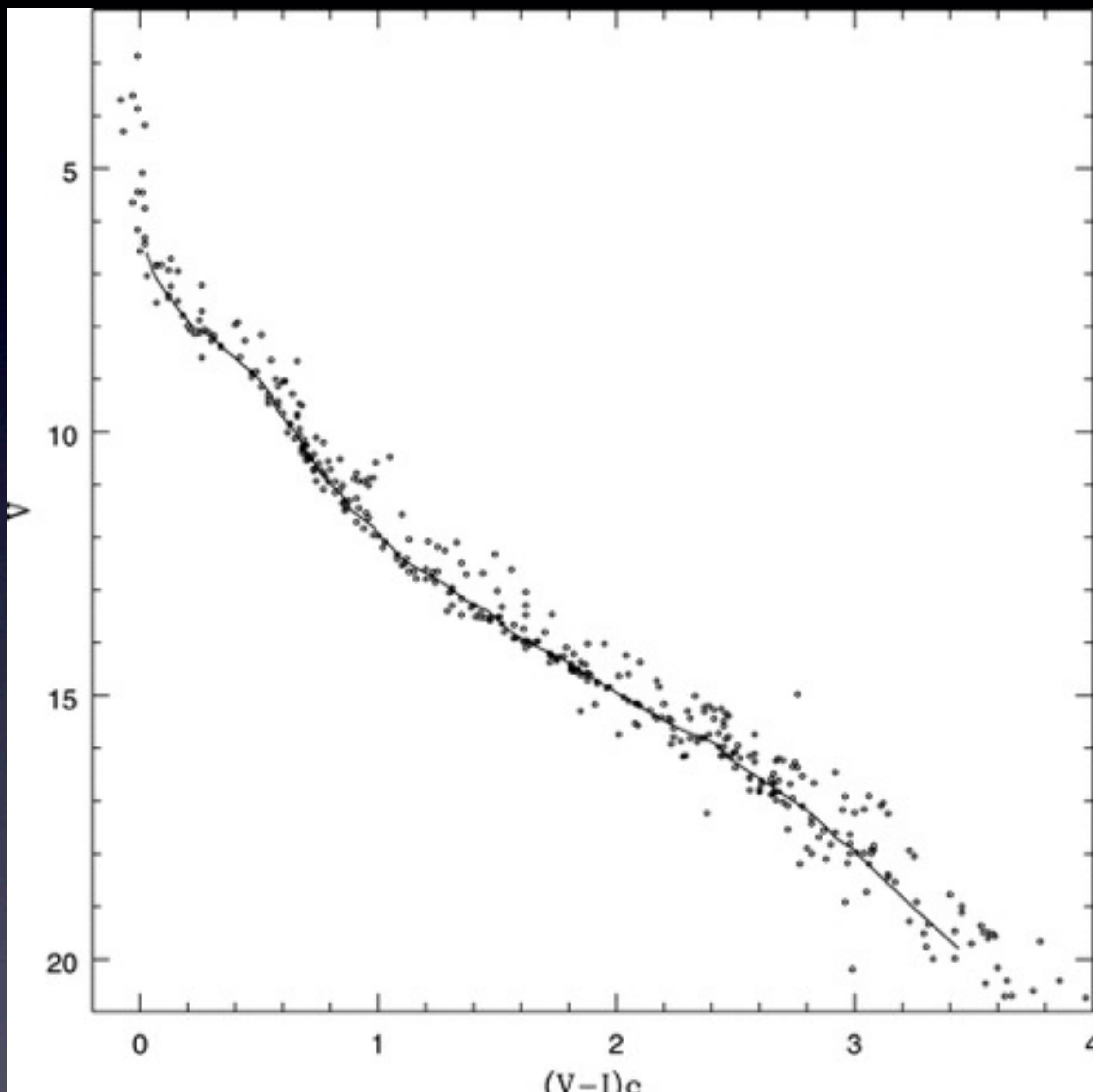

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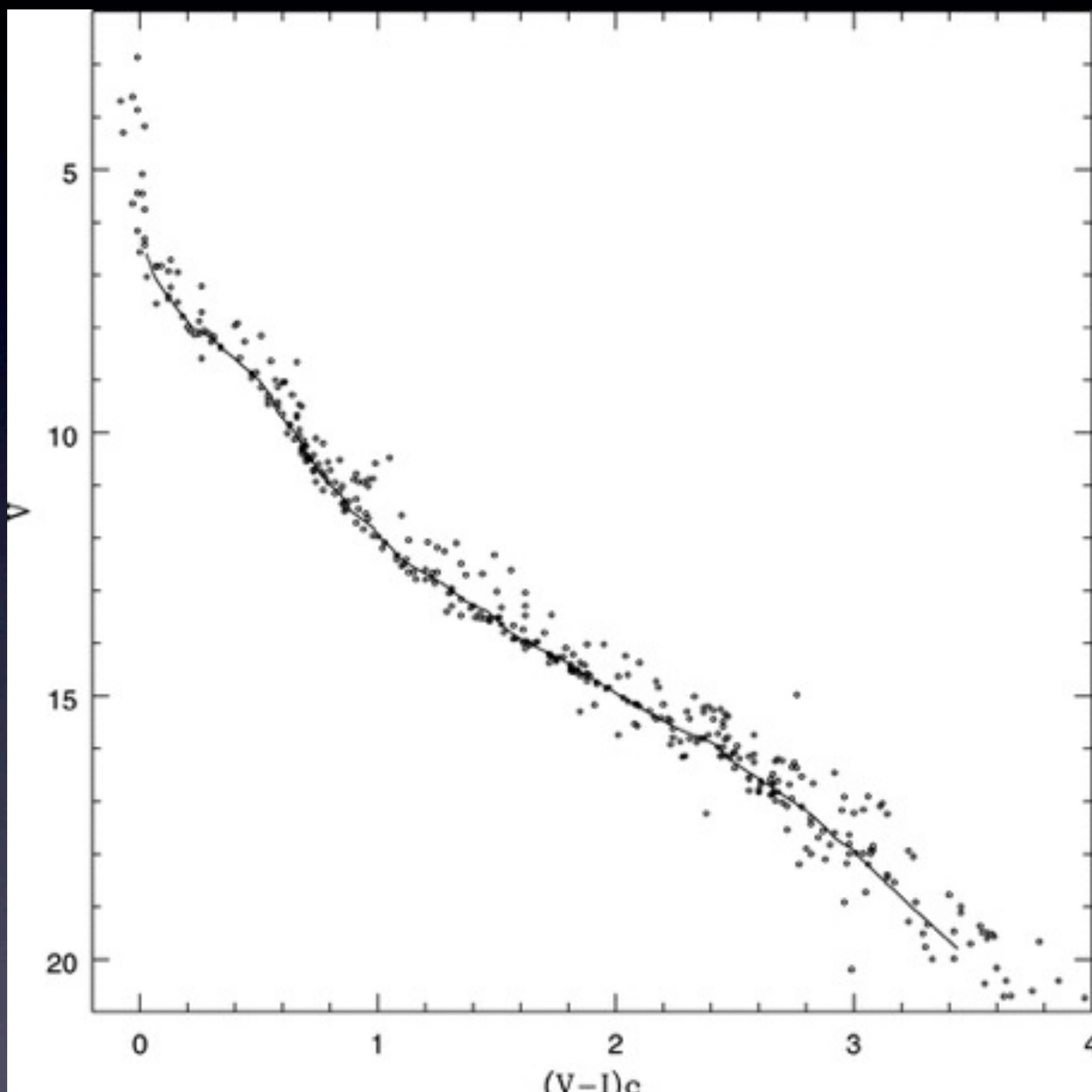
Why not χ^2?

– binaries

Fitting the CMD - The problem



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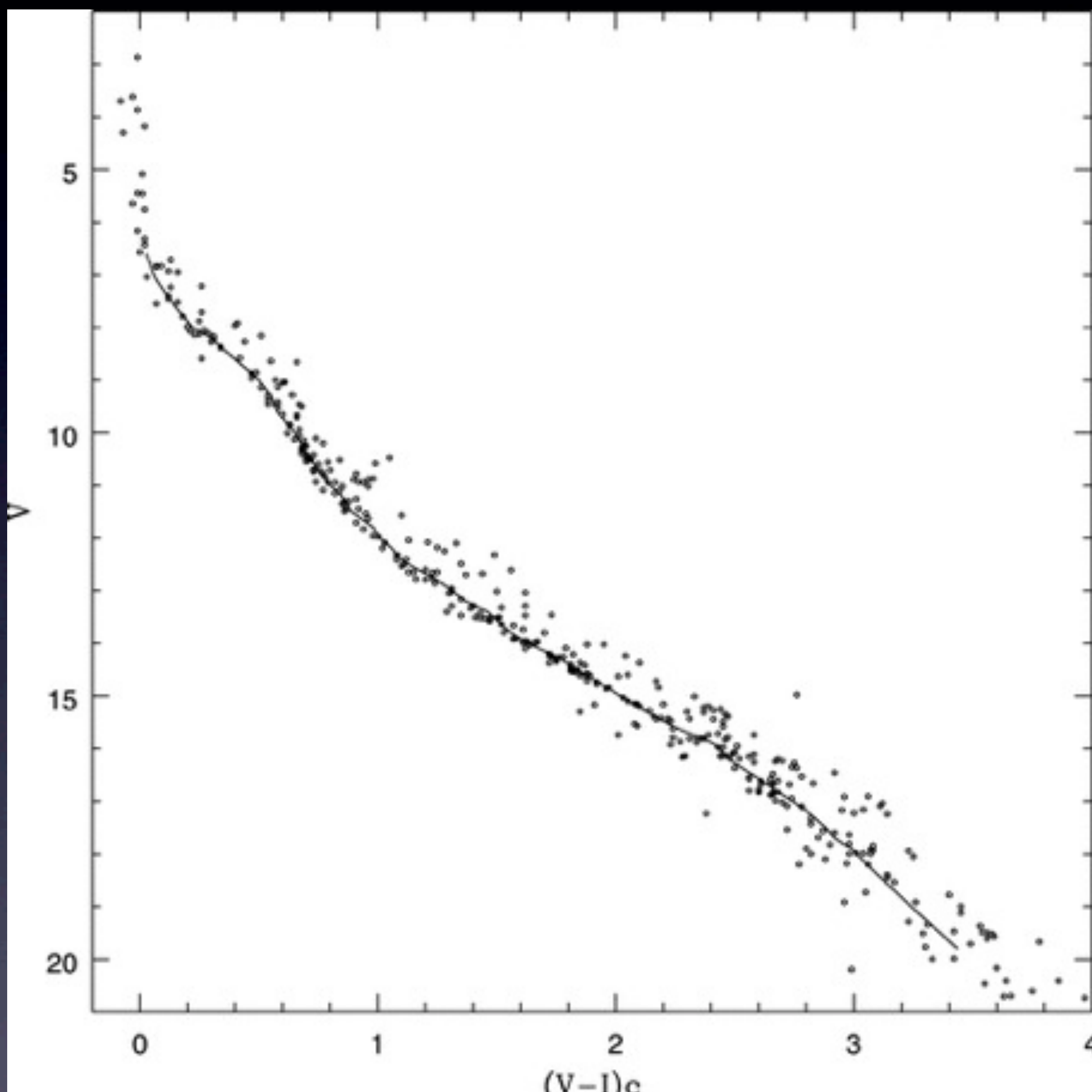
Why not χ^2?

- binaries
- 2D error bars

Fitting the CMD - The problem



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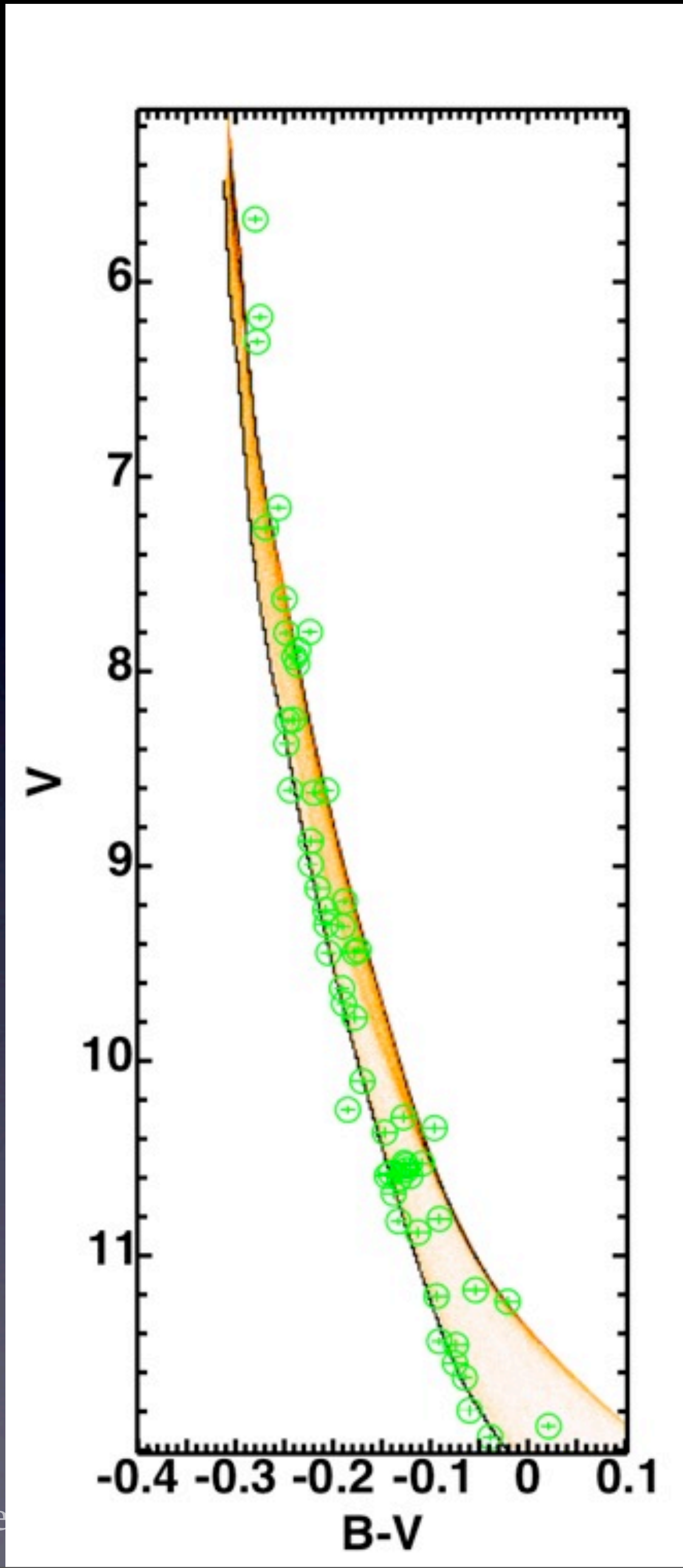
- 2D error bars

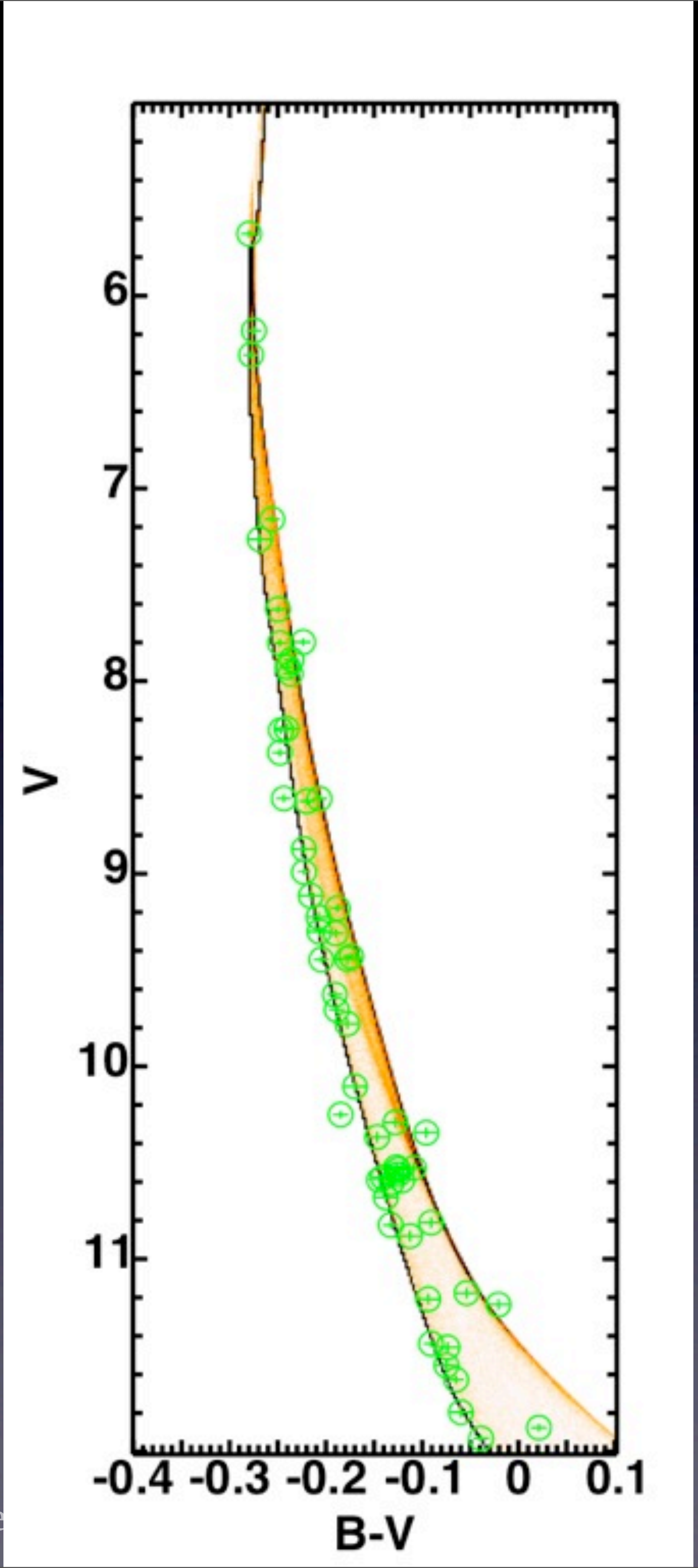
By eye fitting

ZAMS to TAMS Ages



NGC 6530
0.25 Myr (Geneva-Bessell)
$Pr(\tau^2)=0.03$

Naylor (2009)



ZAMS to TAMS Ages

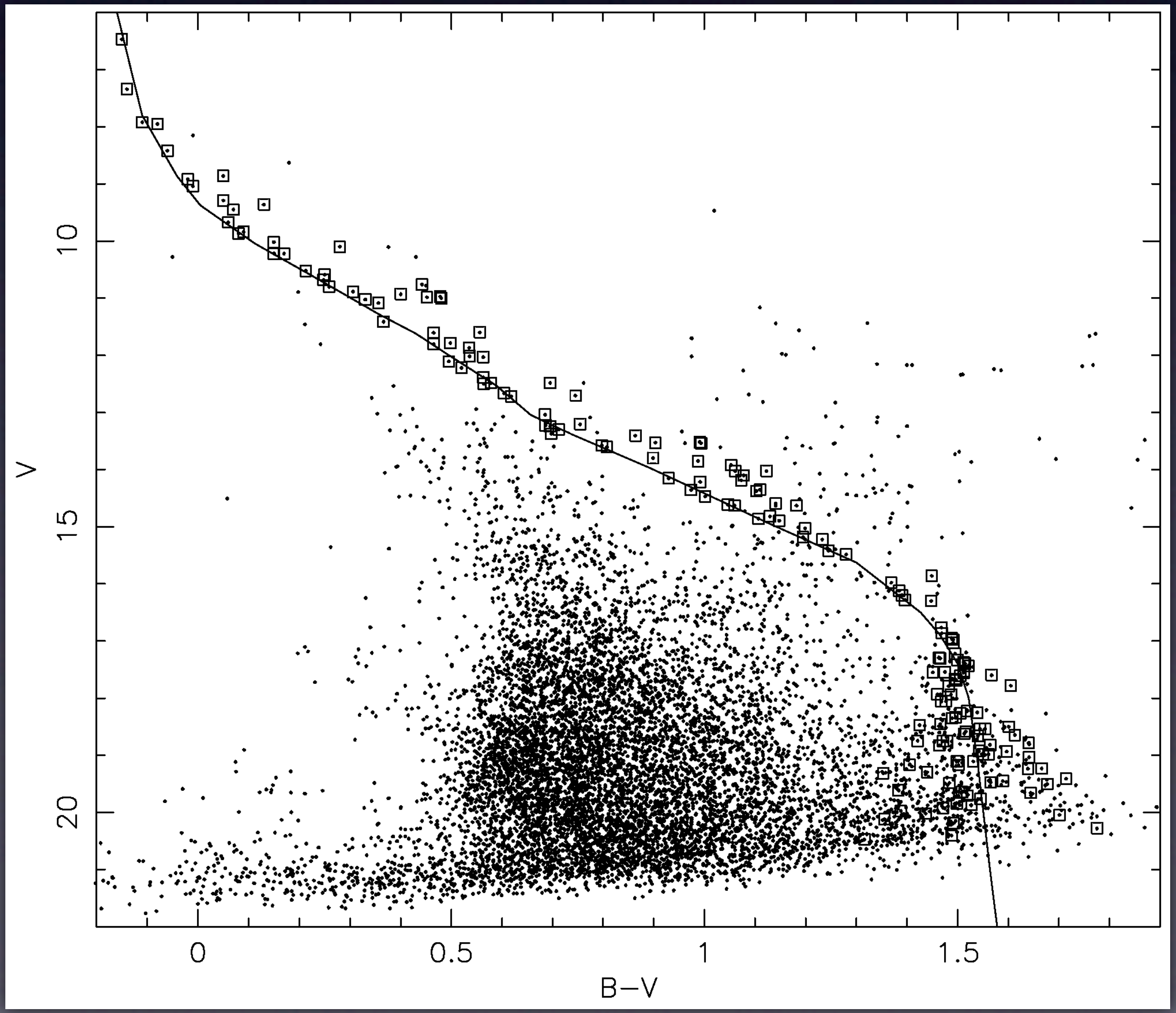
NGC 6530
5.50 Myr (Geneva-Bessell)
$Pr(\tau^2)=0.67$

c.f. 2 Myr PMS isochronal (contraction) age

Naylor (2009)

The PMS age crisis

- Most young cluster ages come from fitting a model to the pre-main-sequence in a CMD.
    - Interior models: luminosity and effective temperature
    - Take model spectra, fold through system bandpasses, predict colours and magnitudes.

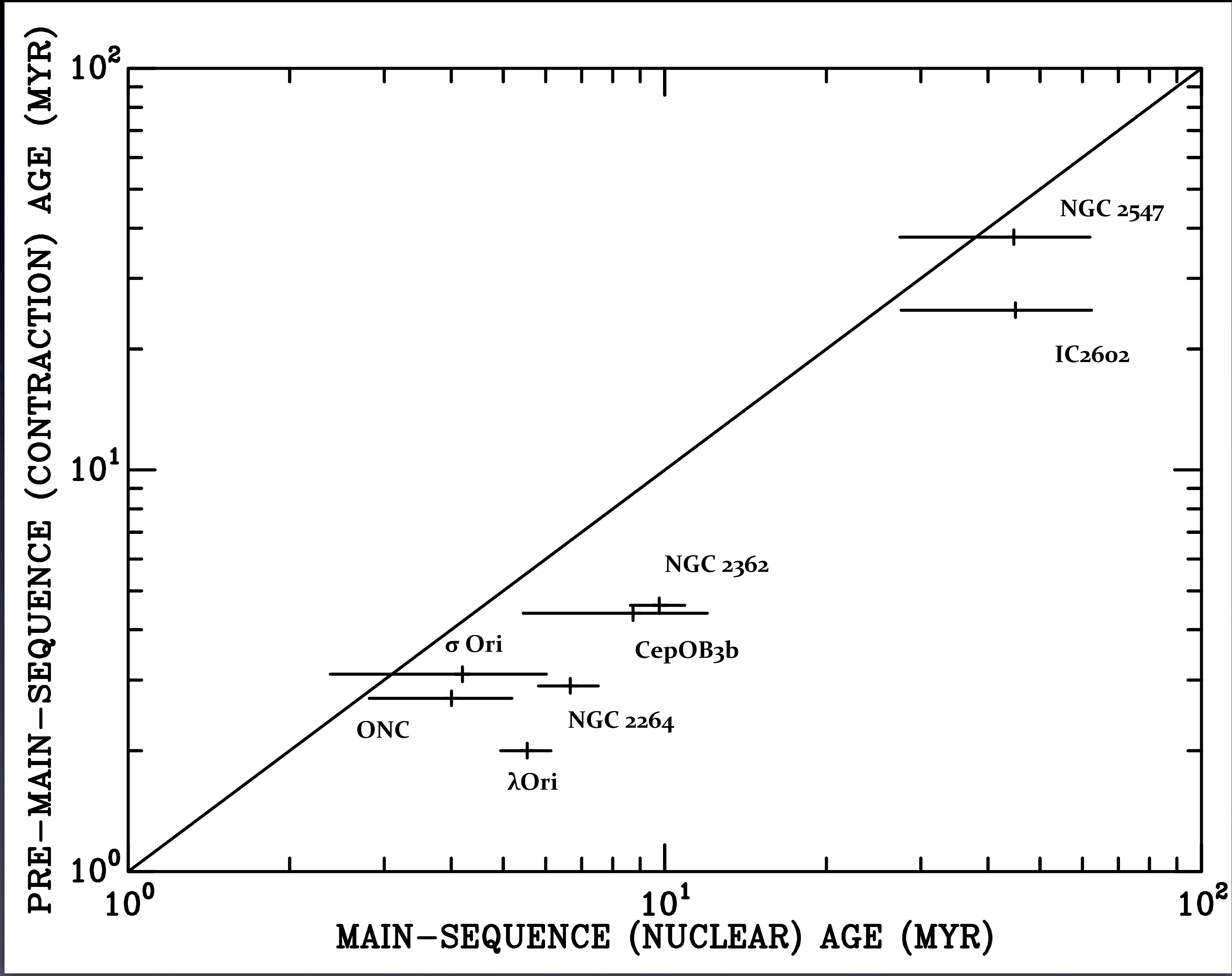


Naylor et al. (2002)

The PMS age crisis

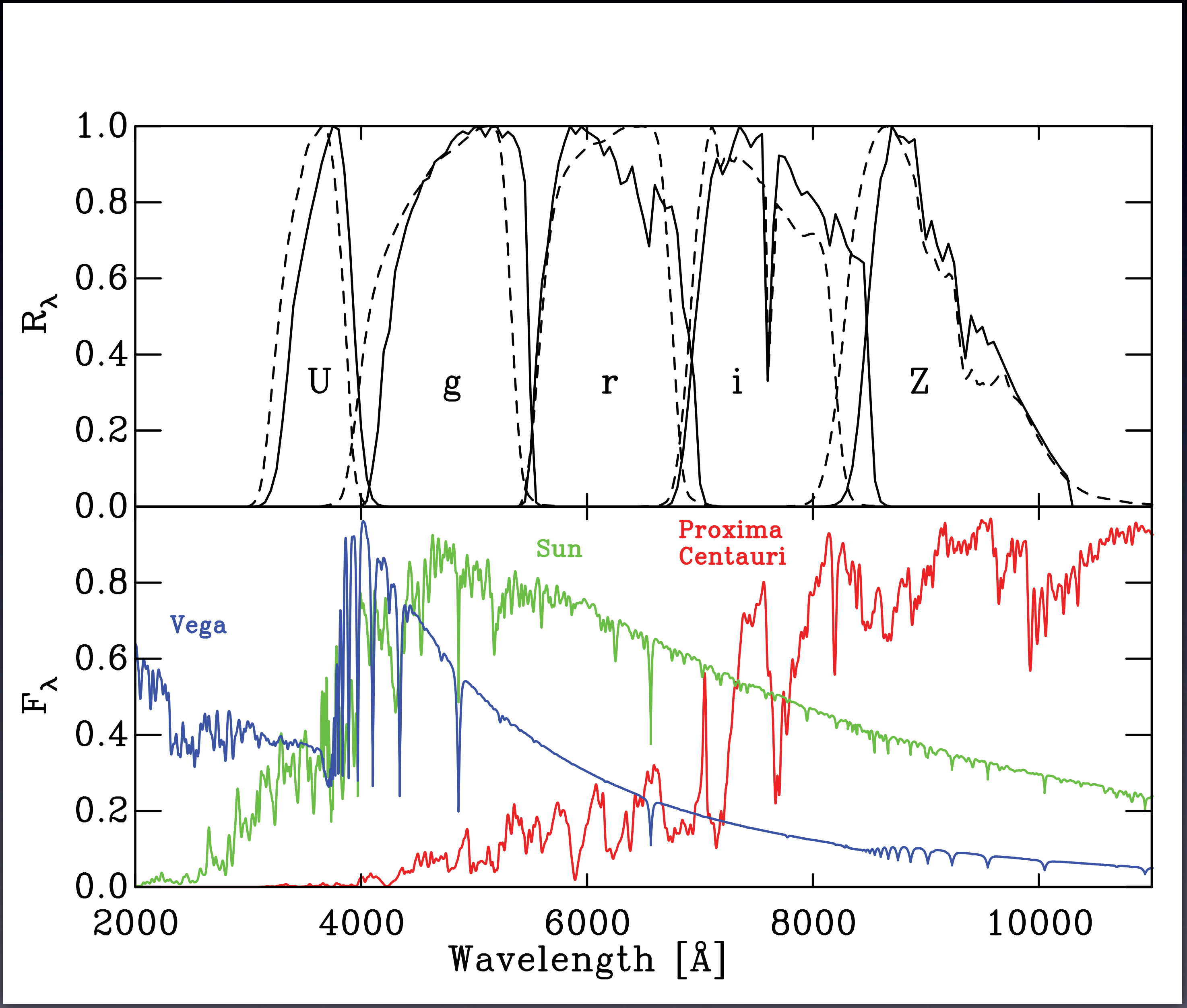
- Most young cluster ages come from fitting a model to the pre-main-sequence in a CMD.
- Different models give different ages.
- Even if you use the same model...
  - different colours give different ages
  - different mass ranges give different ages.
- These differences are large (factor two).

Summary for PMS ages



Naylor (2009)

What's wrong with PMS ages?



Bell et al. (2012)

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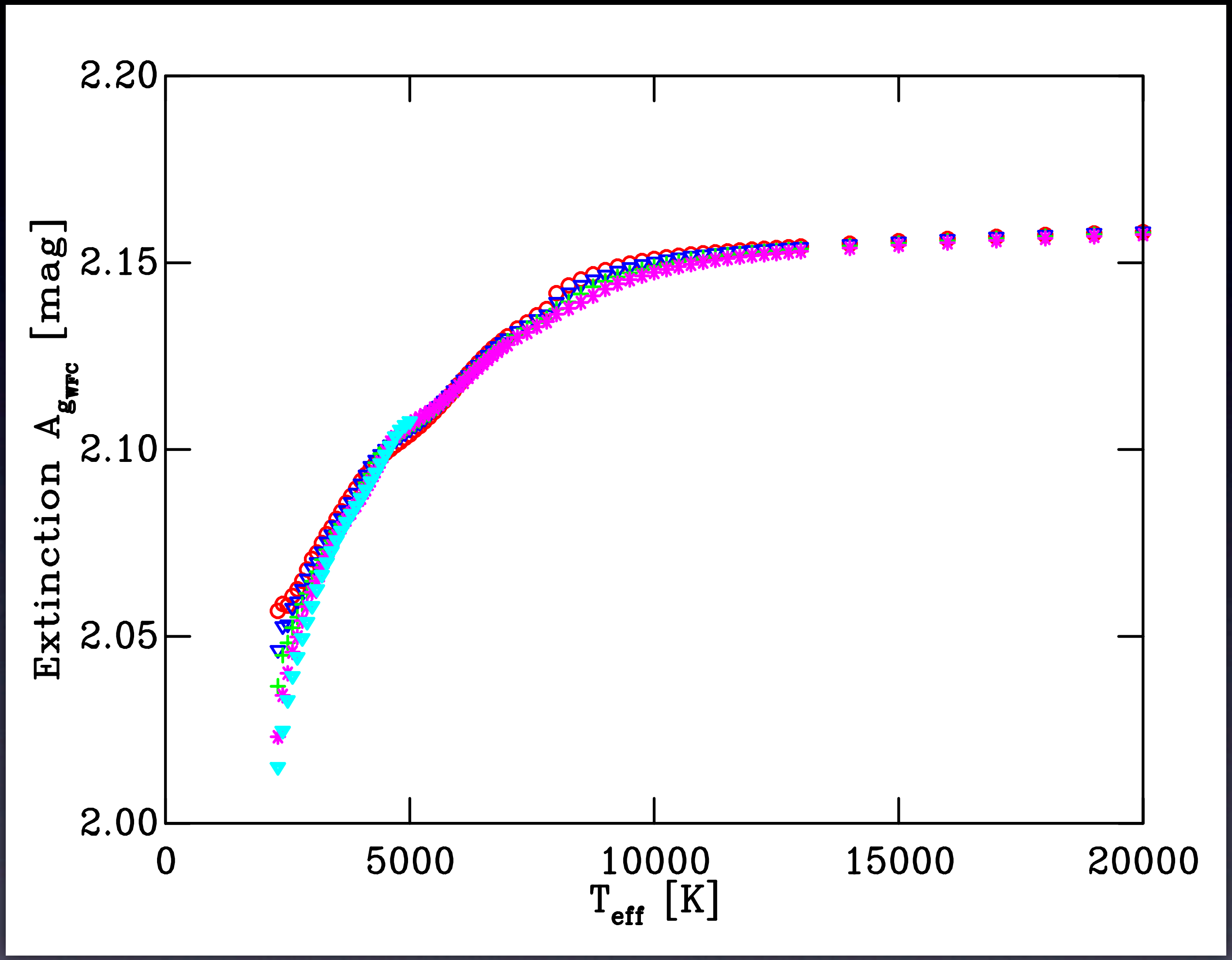
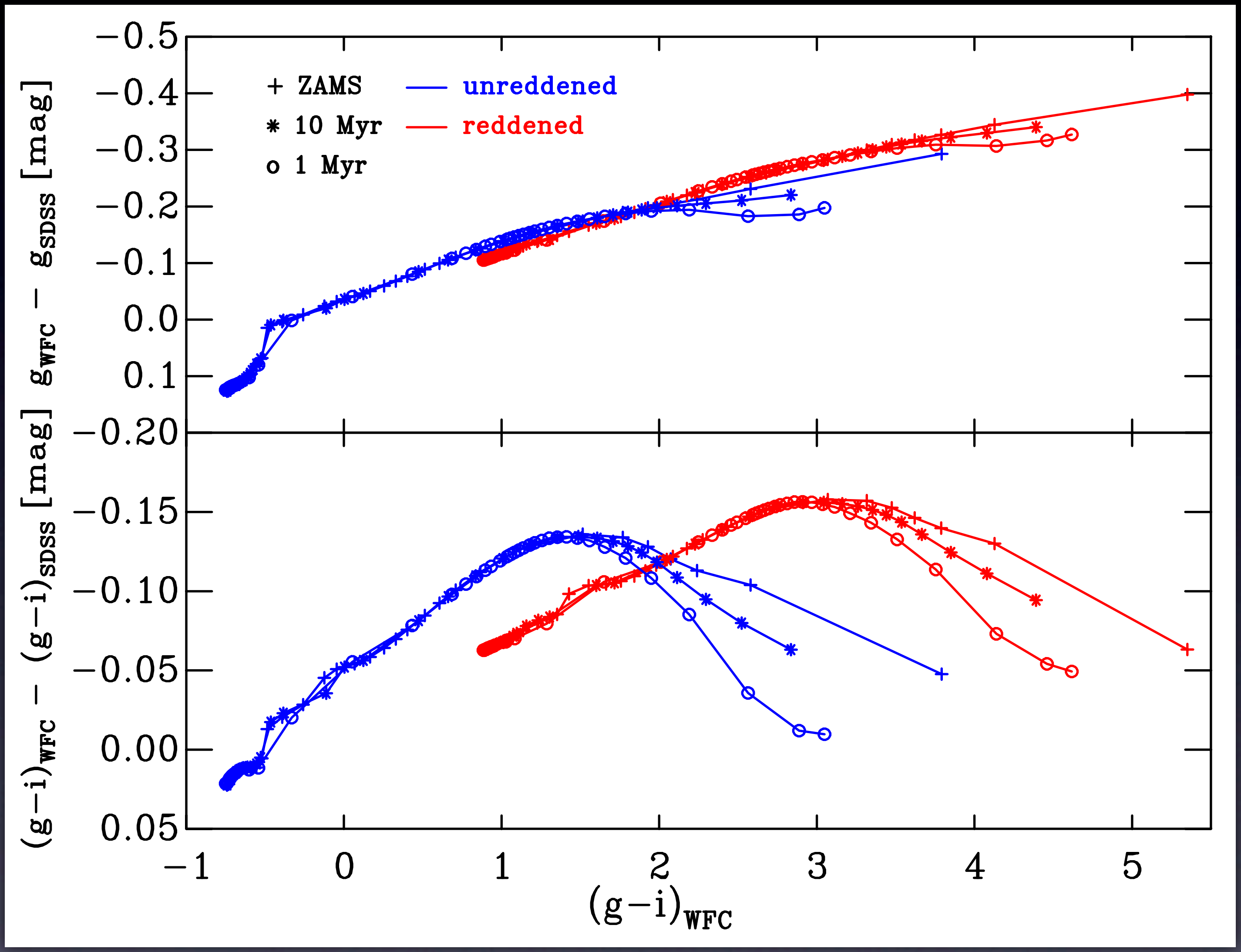


Bell (thesis)

What's wrong with PMS ages?



=> Factor 2 in age!

Bell et al. (2012)

- $g_{stand} = g_{inst} + \phi_g(g\text{-}i)_{inst} - k_g\chi + z_g$???

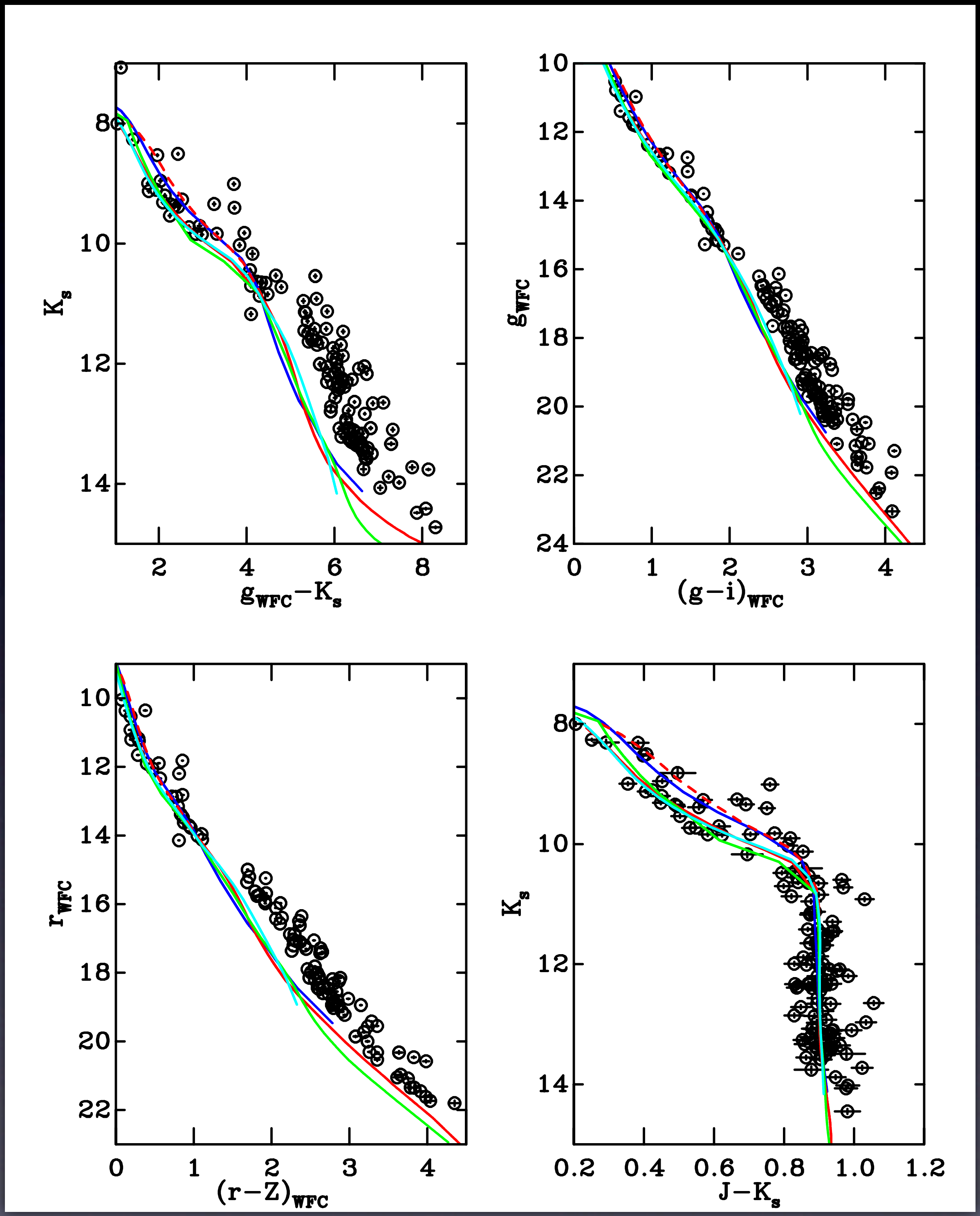
Testing the models - The Sample

- Transformations between systems can introduce large errors.
- So we have a sample of star forming regions all observed with the same filter system and the same standard stars taken with the INT WFC.

Test – Fitting the Pleiades

- Worked out the natural system for the INT WFC from instrument throughputs.
- Age of Pleiades 130Myr (Li boundary, but agrees with ZAMS to TAMS).
- Distance modulus 5.63 (HST parallax, but also agrees with ZAMS fitting).
- Take models, redden them (A_V=0.12), fold through filter responses and....

Test – Fitting the Pleiades

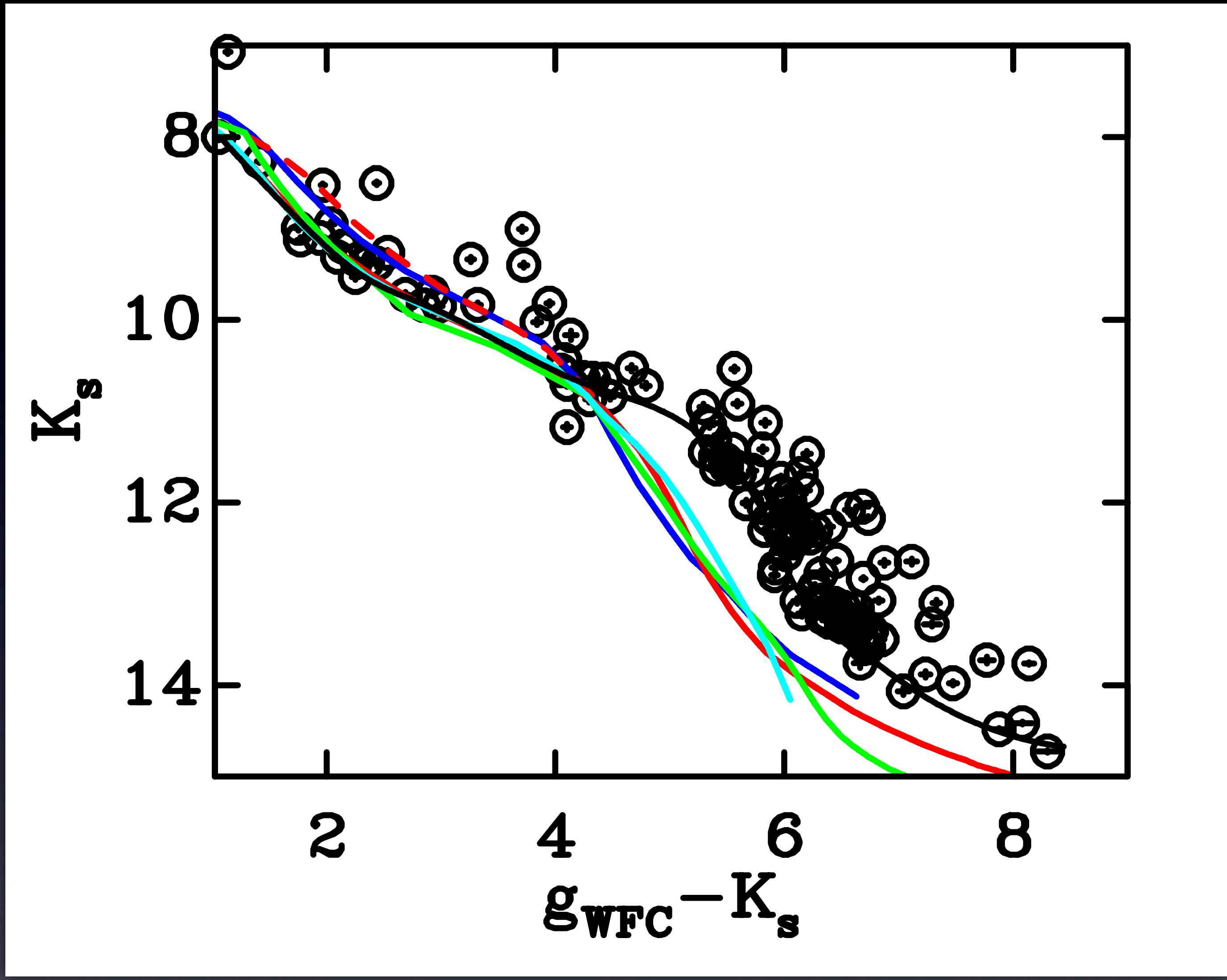


Bell et al. (2012)

- It doesn't work!
- Models too blue
- Potentially missing opacity in the model atmospheres.
- e.g. Stauffer et al. (2007)

Baraffe et al. (1998) red
Siess et al. (2000) blue
D'Antona & Mazzitelli (1997) green
Dotter et al. (2008) cyan

Test – Fitting the Pleiades



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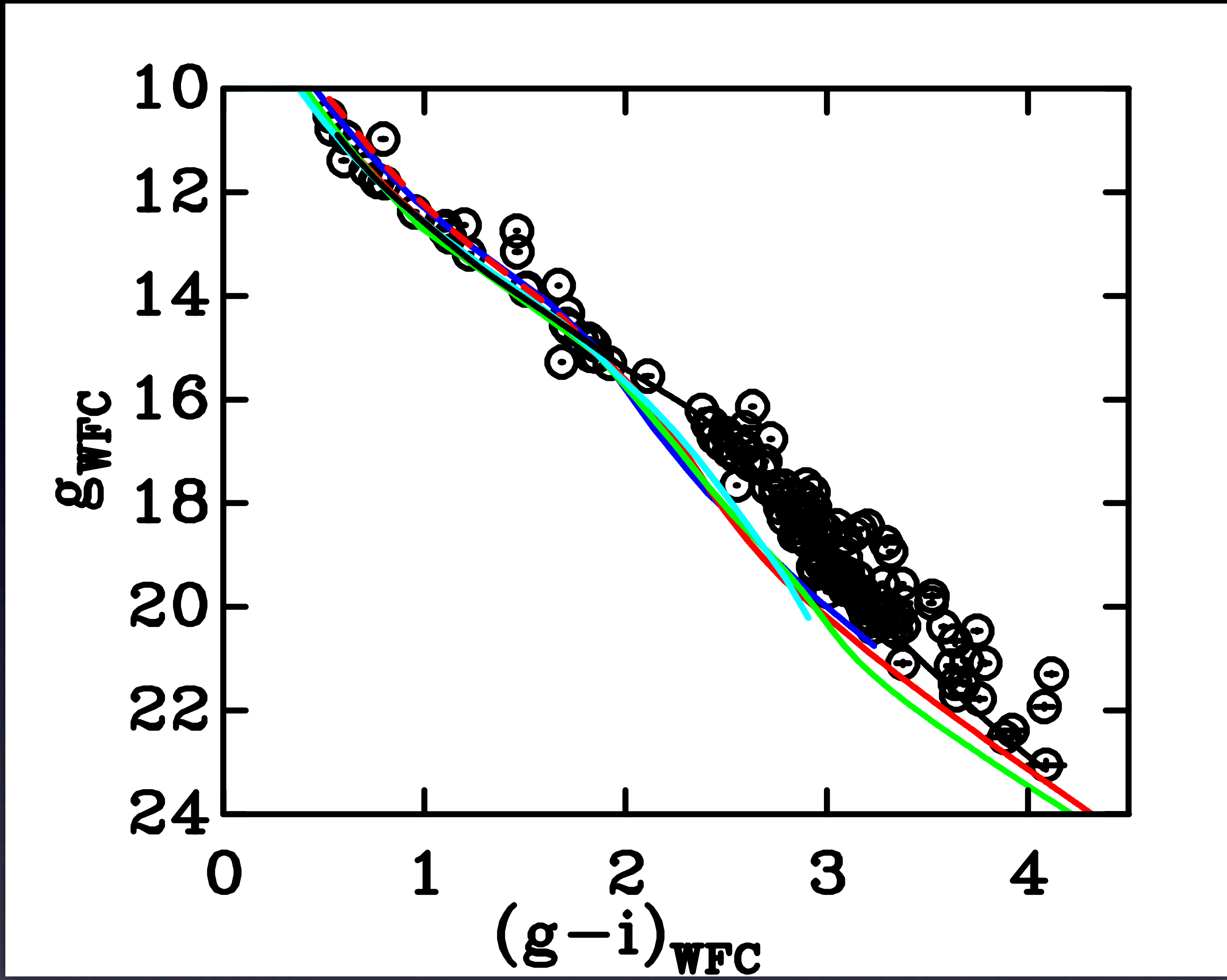

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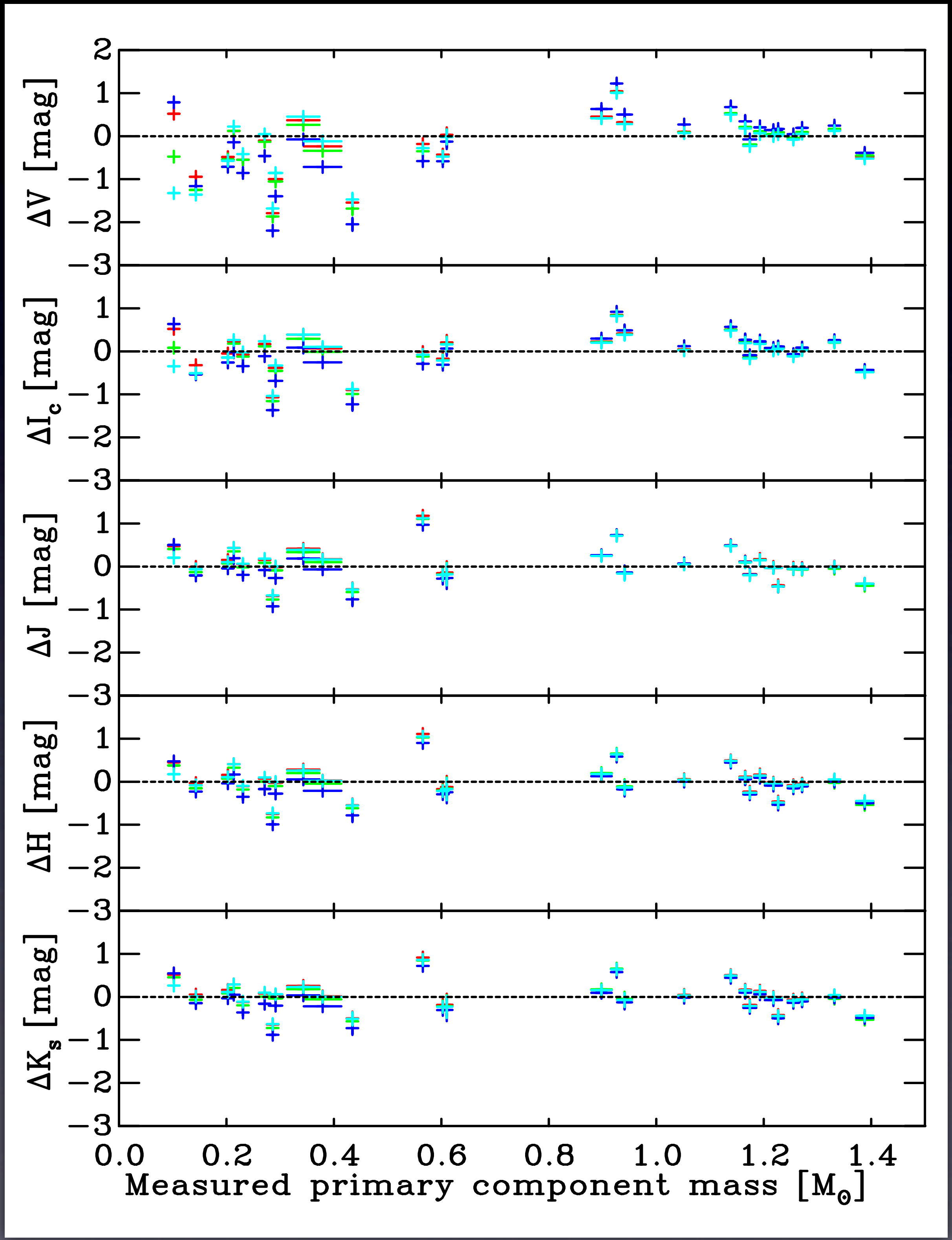
Main-Sequence Binaries

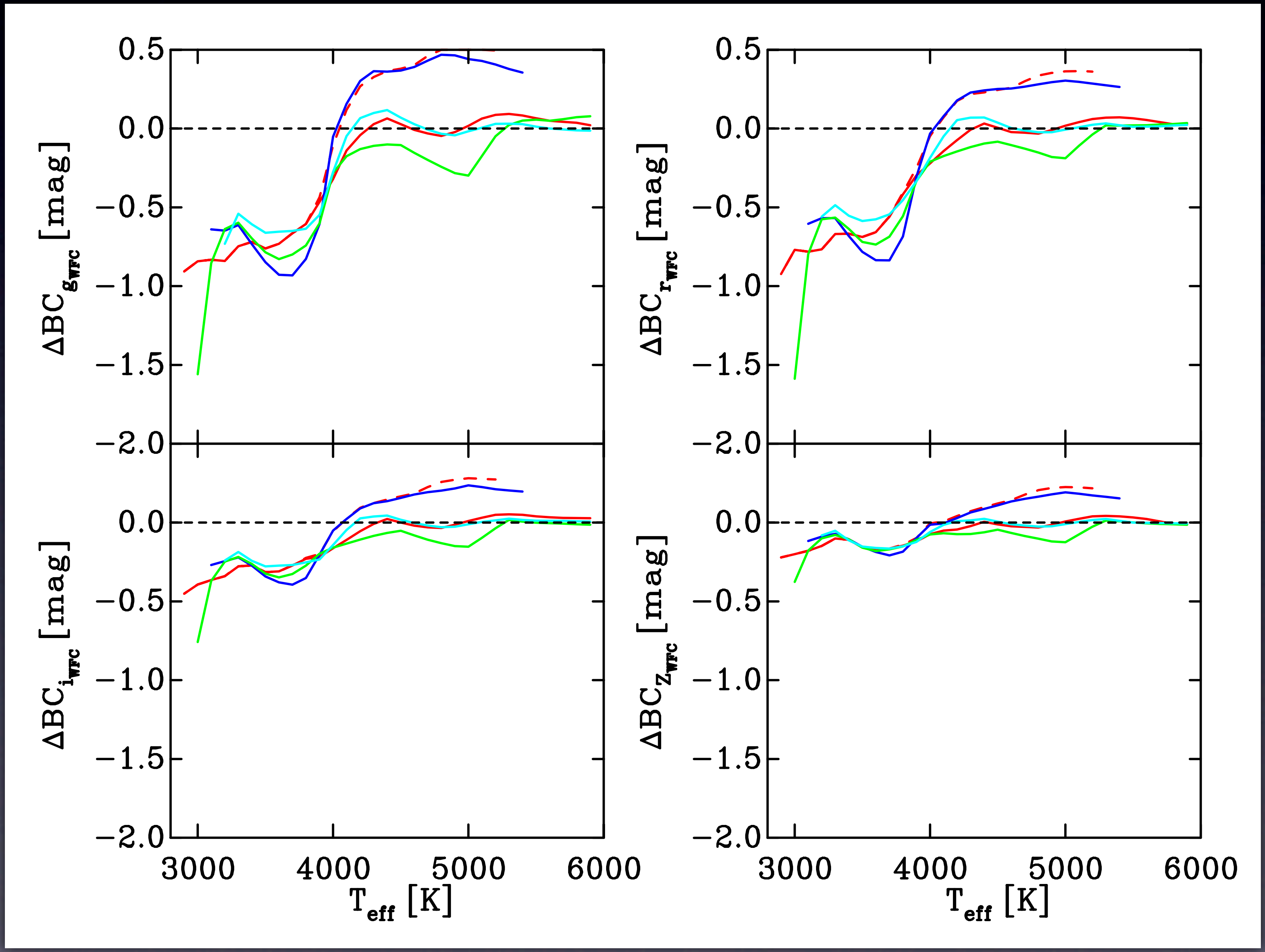


Bell et al. (2012)

Quantifying the discrepancy

- Start with the Pleiades.
- Assume K_s has well modeled flux.
- Calculate the missing opacity for the other bands w.r.t. the model.

Quantifying the discrepancy

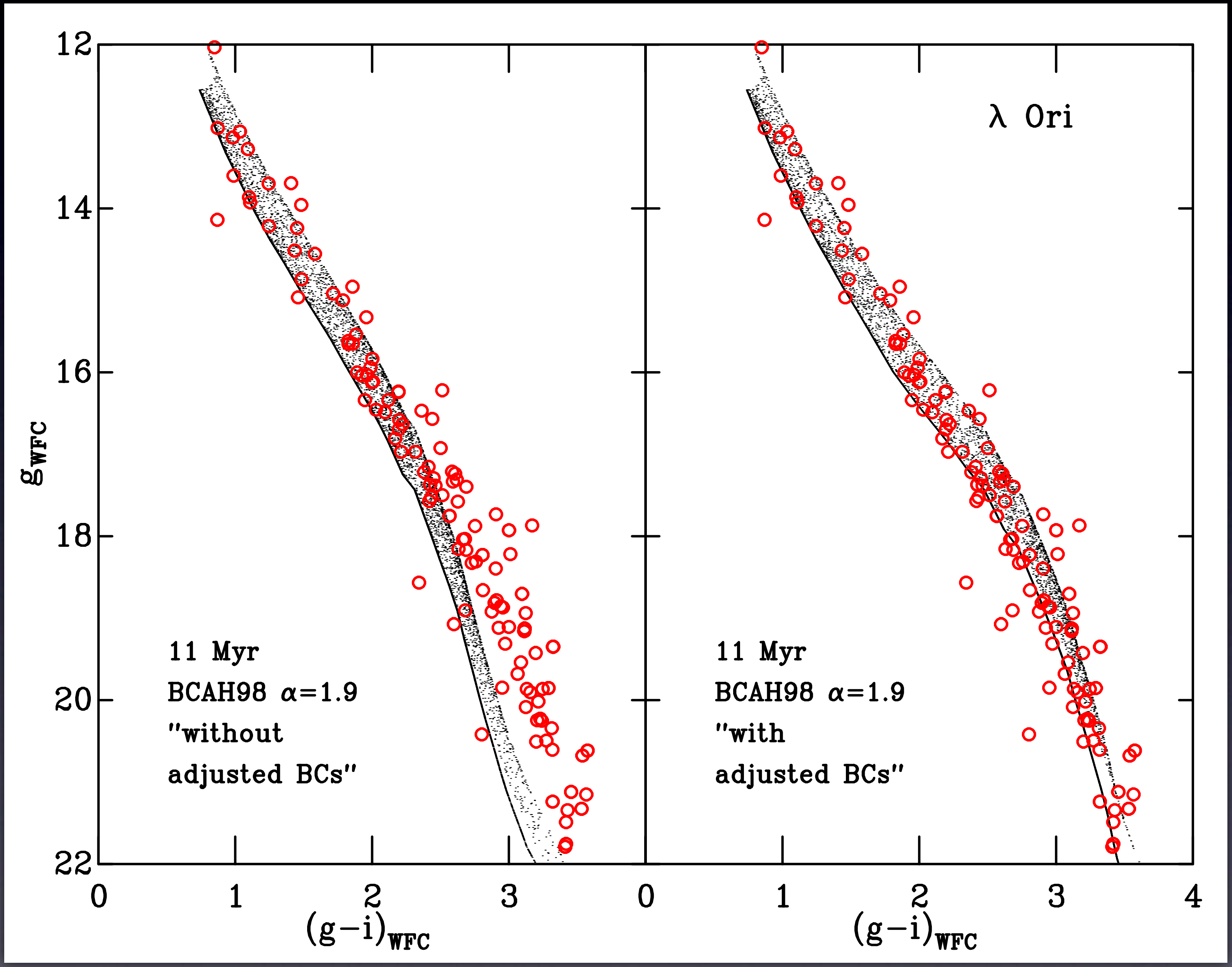


$\Rightarrow$ Factor 2 in age (again)!

Applying the correction

- Take the model spectra, redden them.
- Fold through band passses.
- Apply missing opacity correction.
- Compare with data.
- Derive new PMS ages.
- Note: models still include theoretical gravity correction.

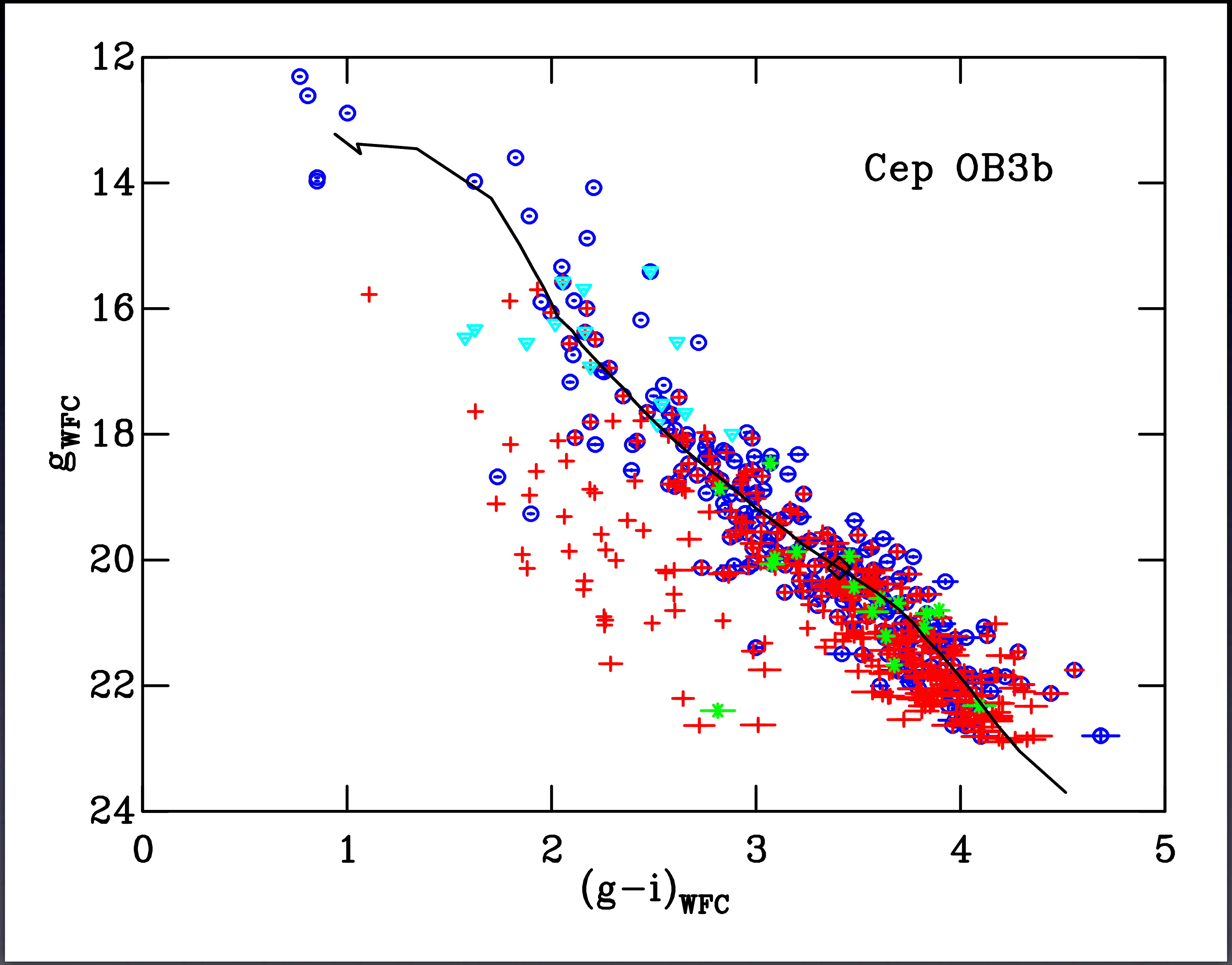
Example Fit for ages > 10Myr



Bell et al. (2013)

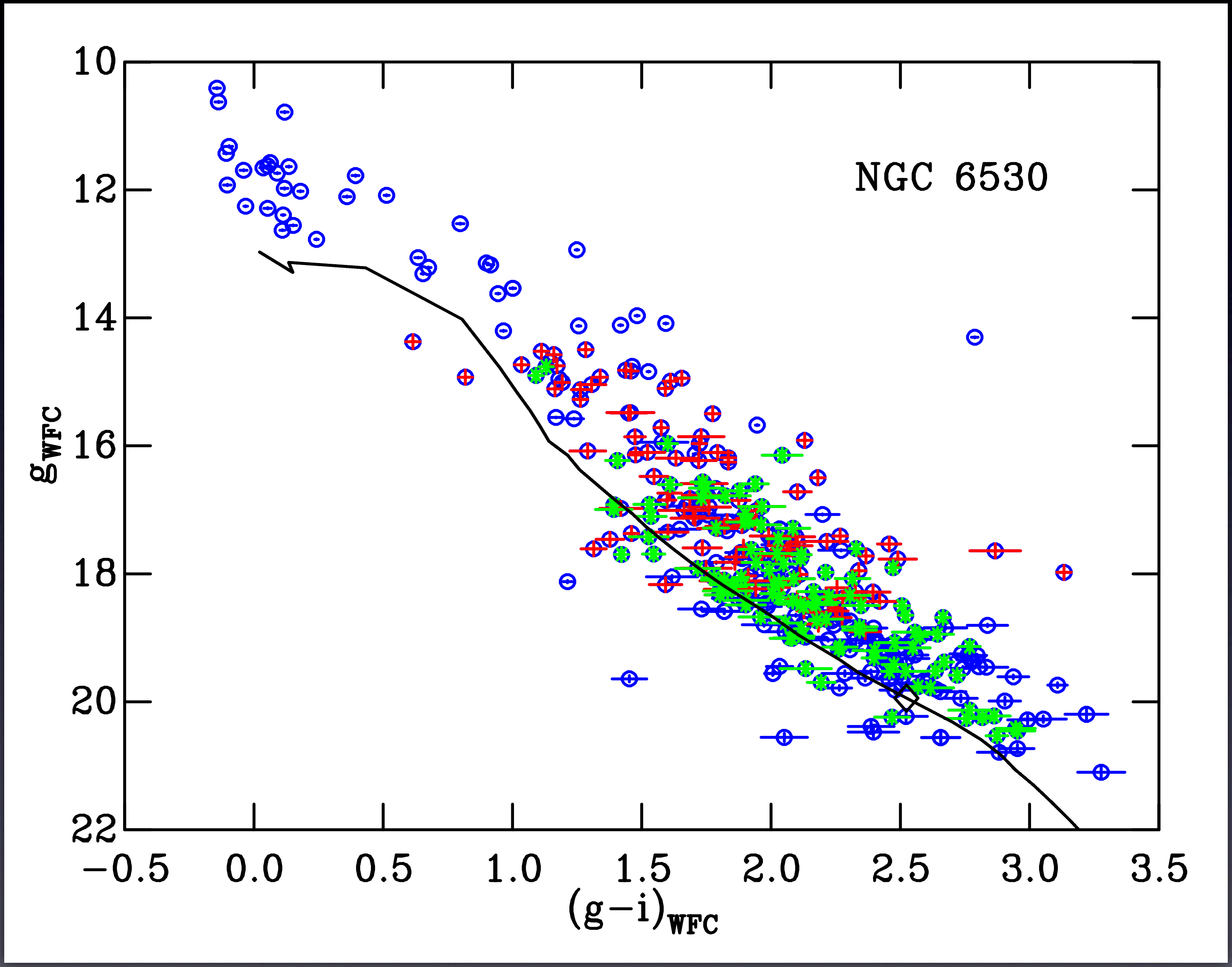
Spectroscopically confirmed members of the λ Ori association from Bayo et al. (2011).

For ages ~6Myr



Bell et al. (2013)

For ages ~2Myr

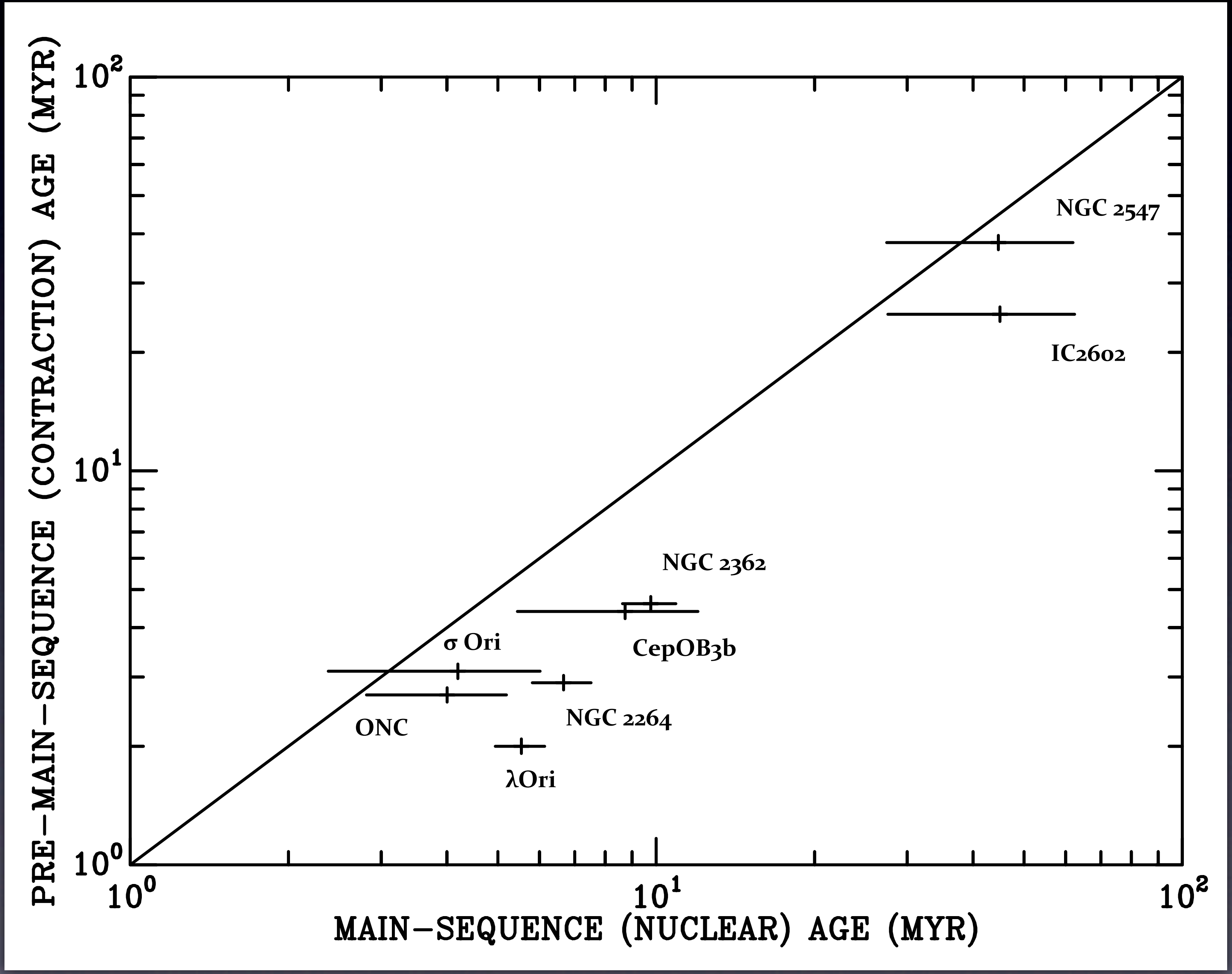


Bell et al. (2013)

Summary for PMS ages

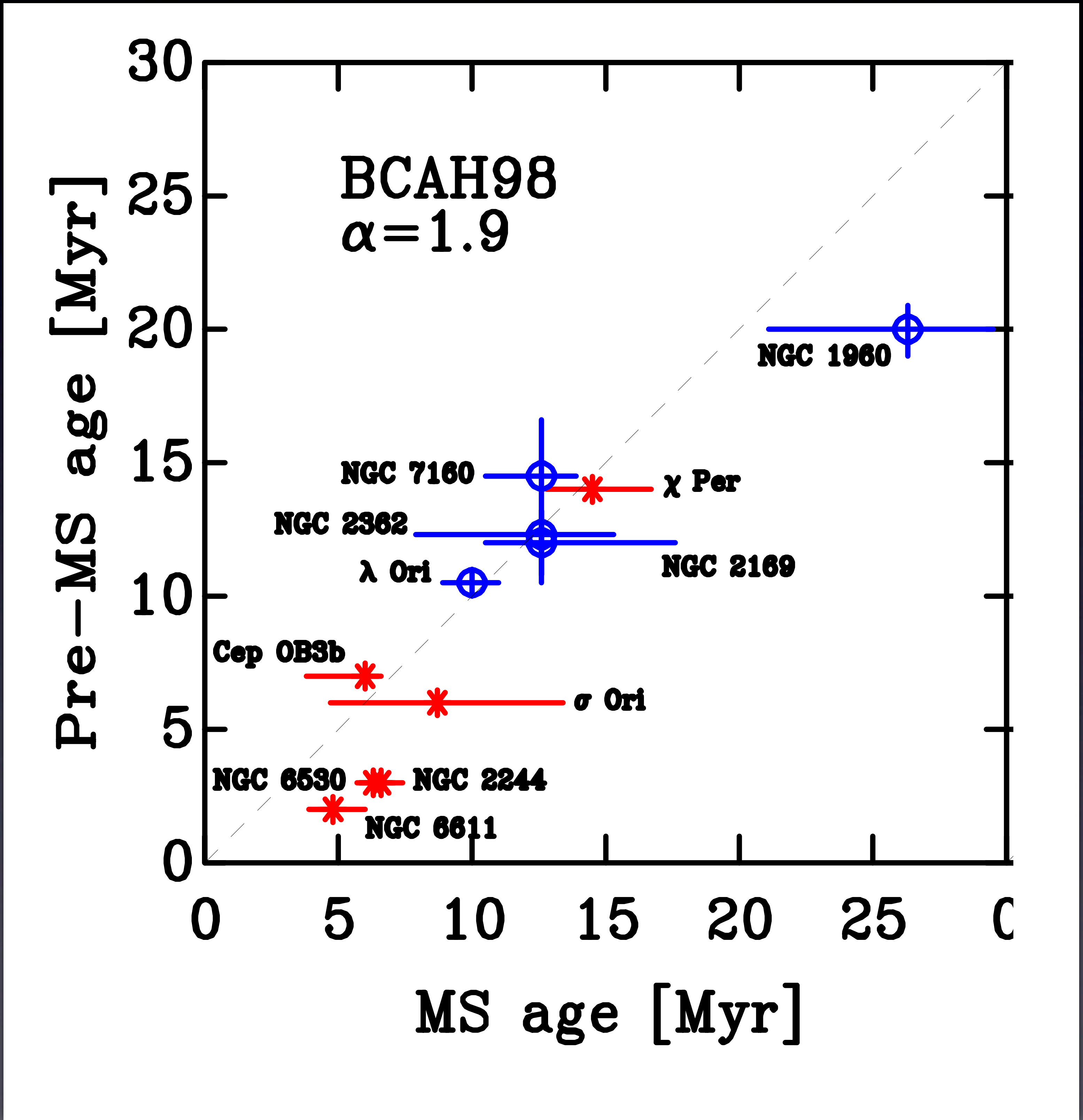
- Older than 10Myr – τ^2 fitting gives age.
- Below this there are spreads in CMD space, but
  - one group around 6Myr with middling spread and
  - one group around 2Myr with large spread.
- But now need to compare with MS ages.

Summary for PMS ages



Naylor (2009)

Summary for PMS ages

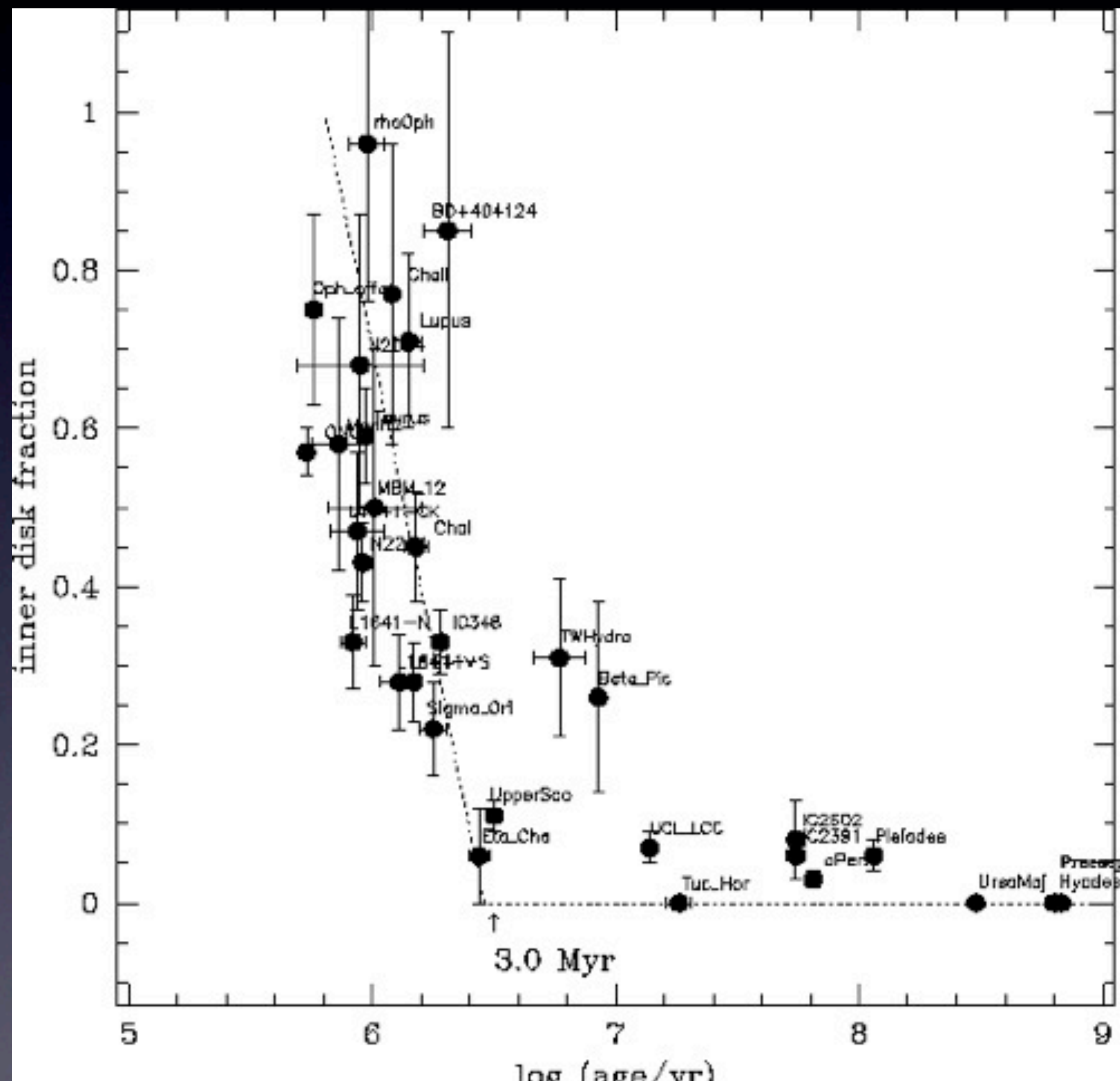


Bell et al. (2013)

Summary for PMS ages

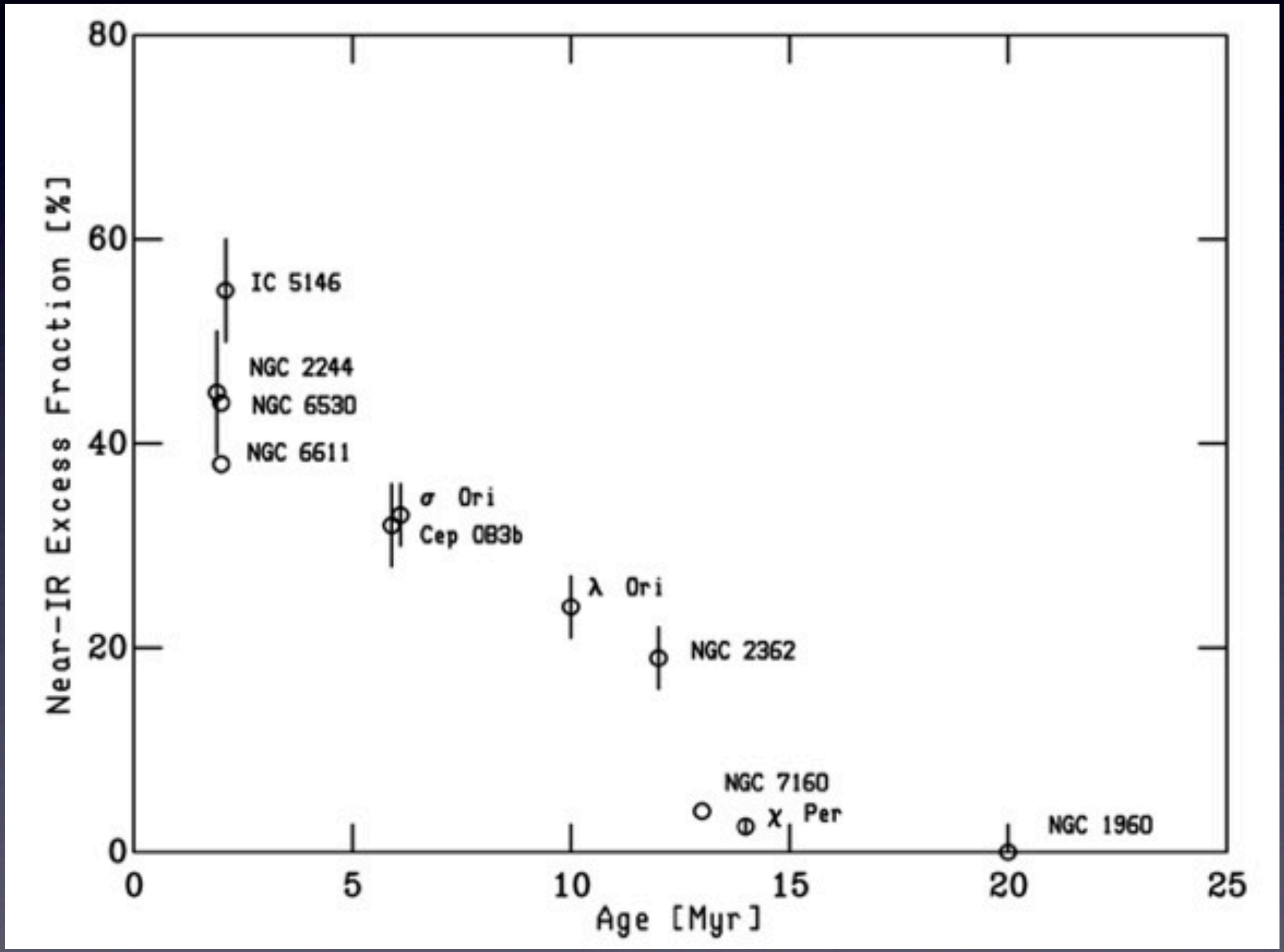
Age (Myr)	SFR	Distance modulus dm	$E(B-V)$
2	NGC 6611 (Eagle Nebula; M 16)[1]	$11.30 \leq 11.38 \leq 11.44$	0.71
	IC 5146 (Cocoon Nebula)[1]	$9.62 \leq 9.81 \leq 10.01$	0.75
	NGC 6530 (Lagoon Nebula; M 8)[1]	$10.59 \leq 10.64 \leq 10.68$	0.32
	NGC 2244 (Rosette Nebula)[1]	$10.67 \leq 10.70 \leq 10.75$	0.43
6	σ Ori[1]	$7.99 \leq 8.05 \leq 8.11$	0.05
	Cep OB3b[1]	$8.70 \leq 8.78 \leq 8.84$	0.89
	IC 348[1]	$6.89 \leq 6.98 \leq 7.17$	0.69
9	NGC 2169	$9.90 \leq 9.99 \leq 10.06$	0.16
10	λ Ori (Collinder 69)[1]	$7.99 \leq 8.02 \leq 8.06$	0.11
12	NGC 2362	$10.57 \leq 10.60 \leq 10.66$	0.07
13	NGC 7160[1]	$9.62 \leq 9.67 \leq 9.76$	0.37
14	χ Per (NGC 884)[1]	$11.77 \leq 11.80 \leq 11.86$	0.52
20	NGC 1960 (M 36)	$10.28 \leq 10.33 \leq 10.35$	0.20

Summary for PMS ages



Credit: Lynn Hillenbrand

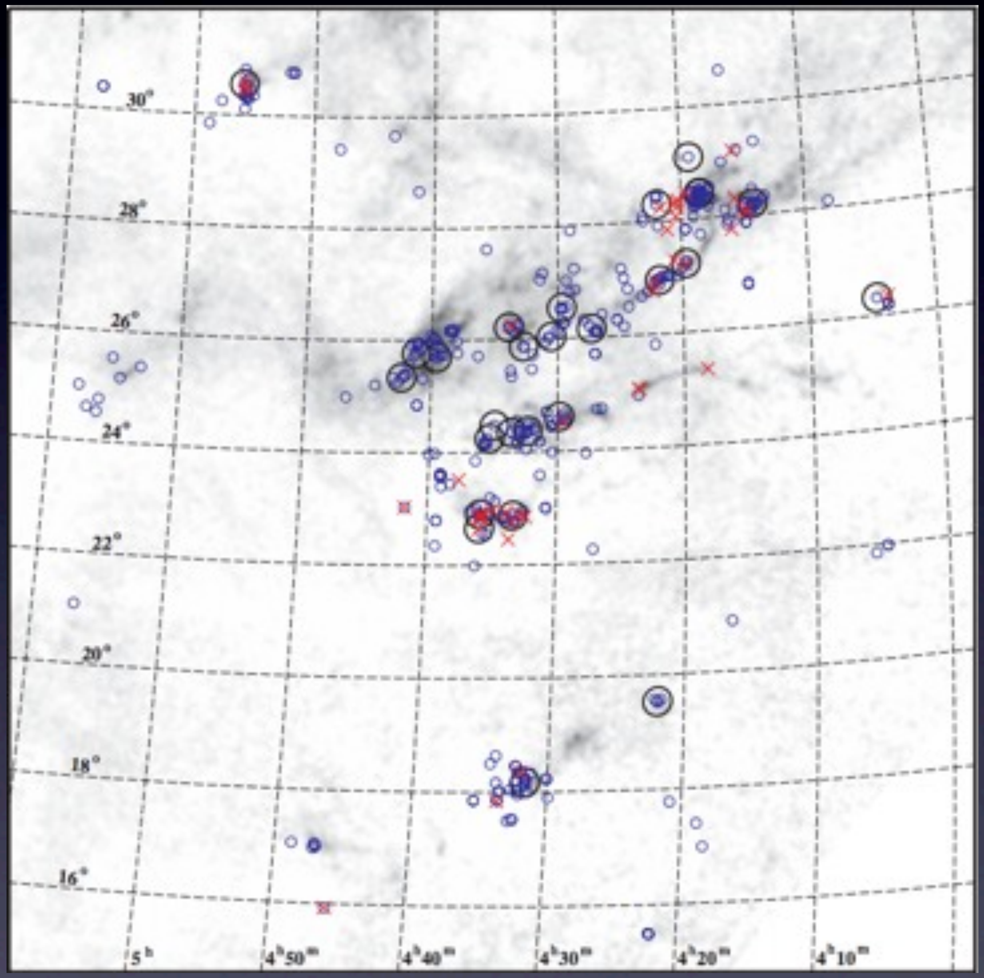
Summary for PMS ages



Bell et al. (2013)

Taurus – the problem child

- Nearest star-forming region.
- Young (~1Myr?)
- Should be good example of low density environment.
  - Is the disc fraction different?
- But the extinction is a nightmare…

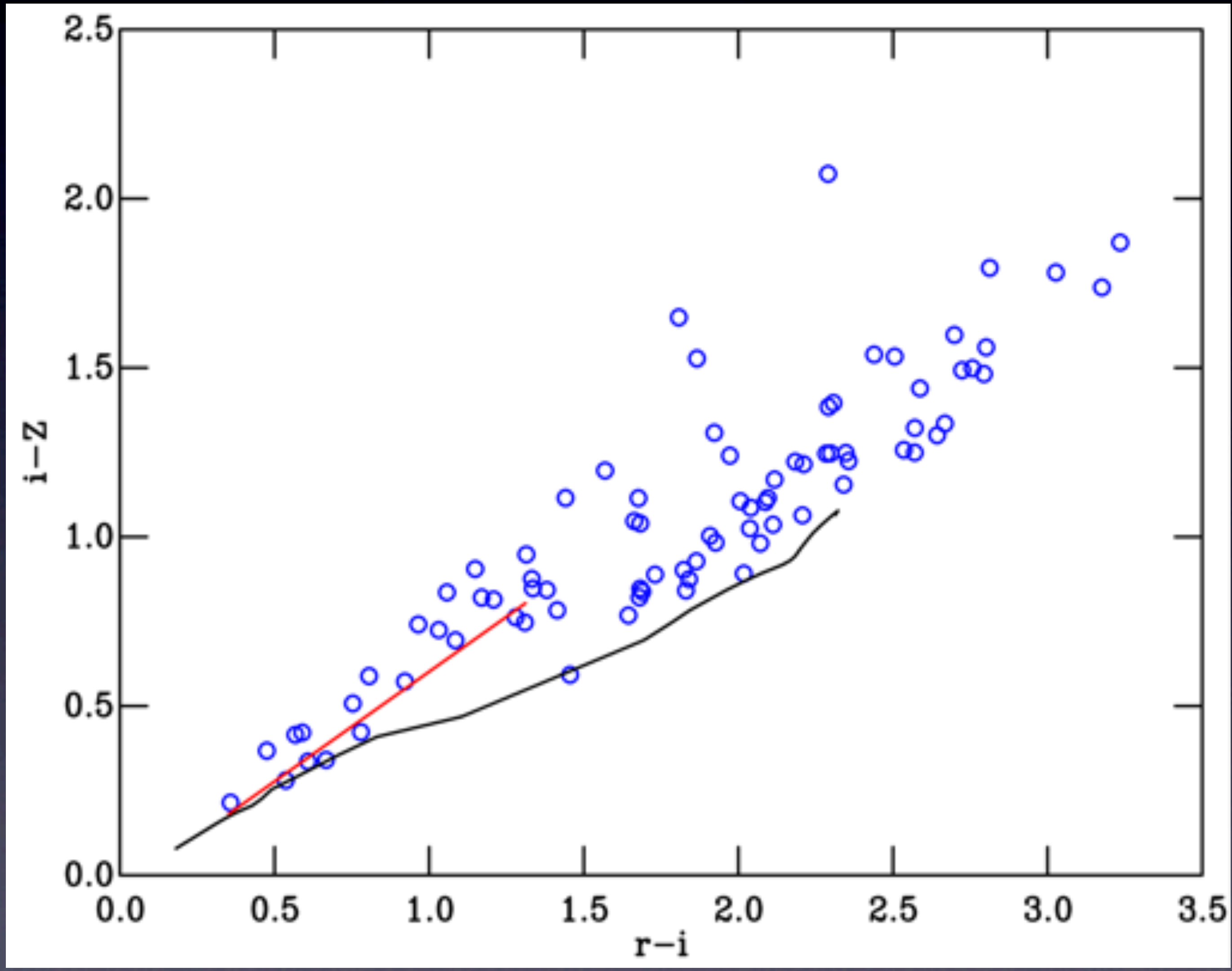


Luhman et al. (2009)

Dereddening

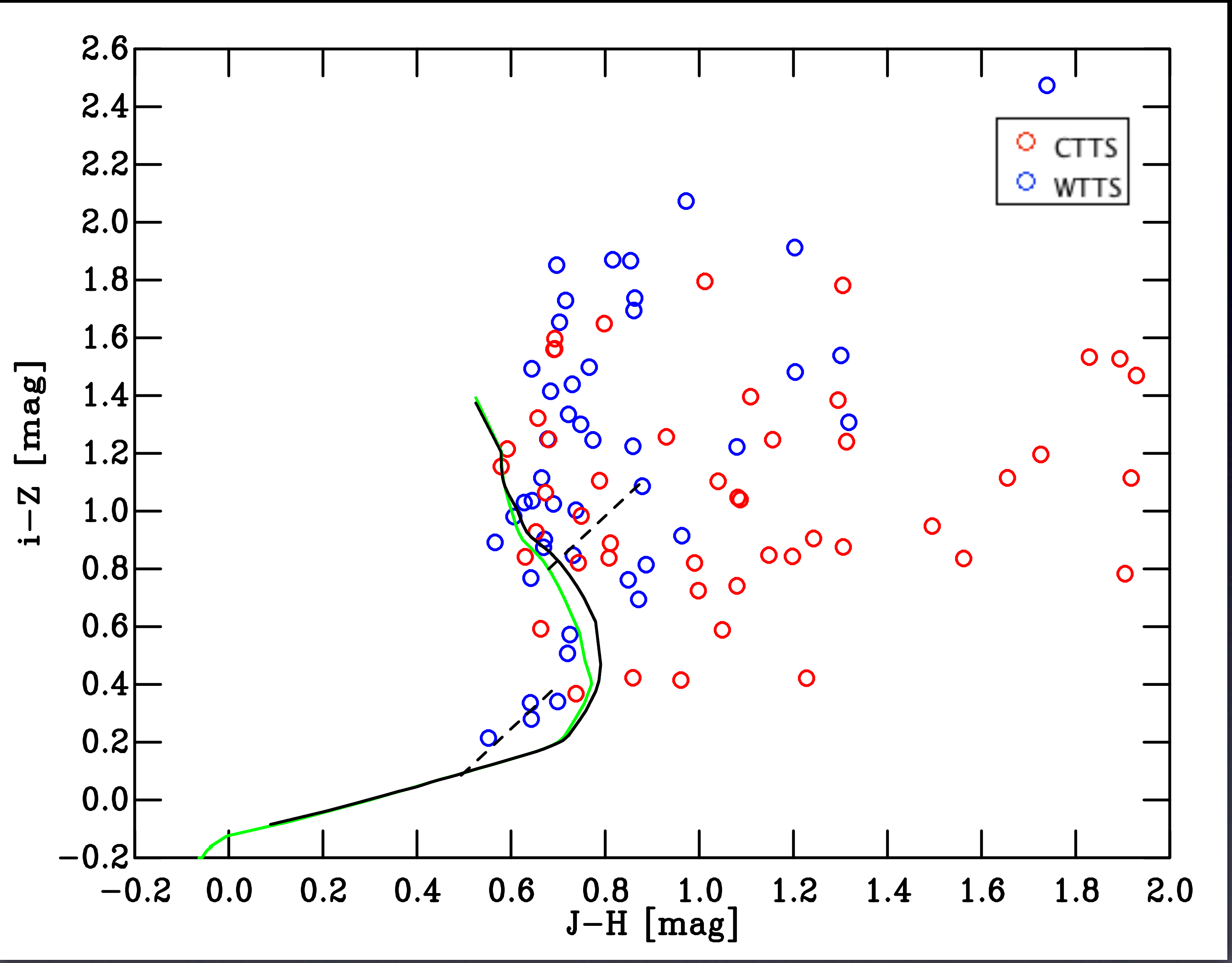
- Reddening vectors usually parallel to sequence

- Colours are degenerate - unable to deredden photometrically

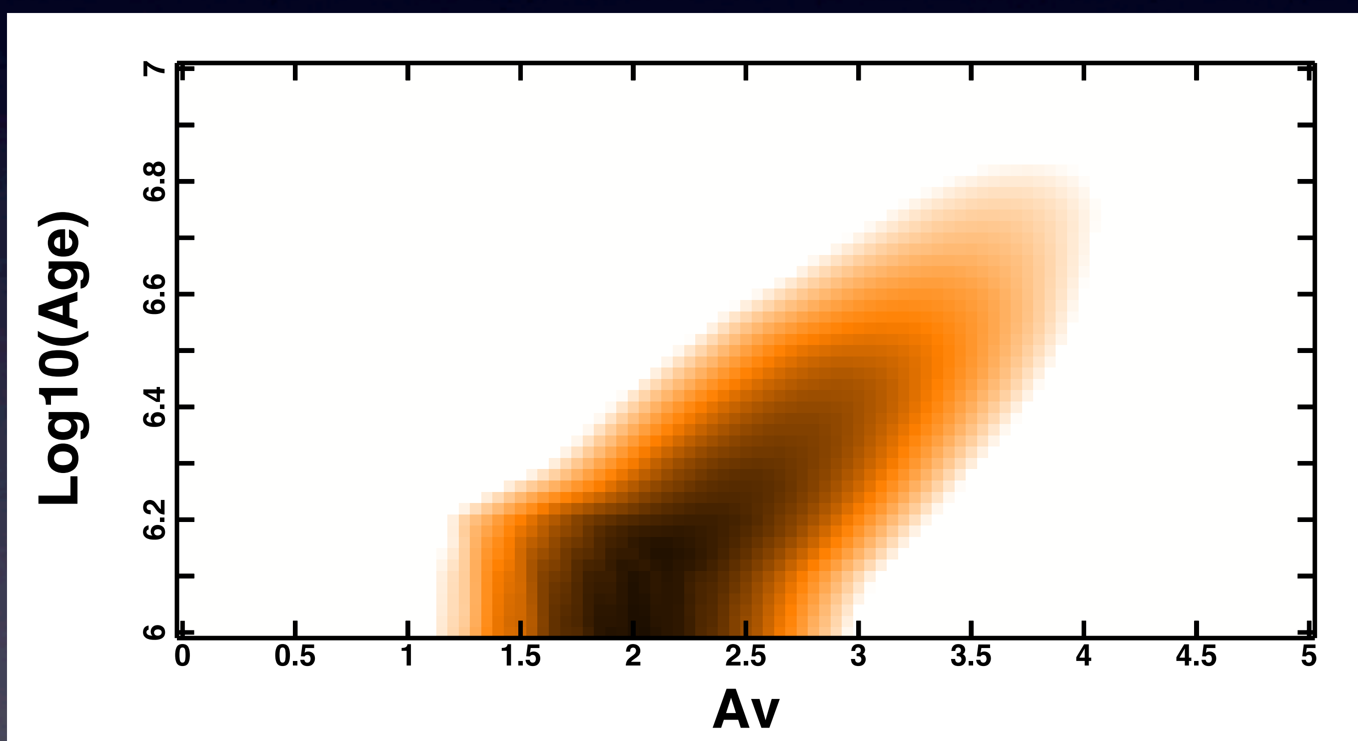


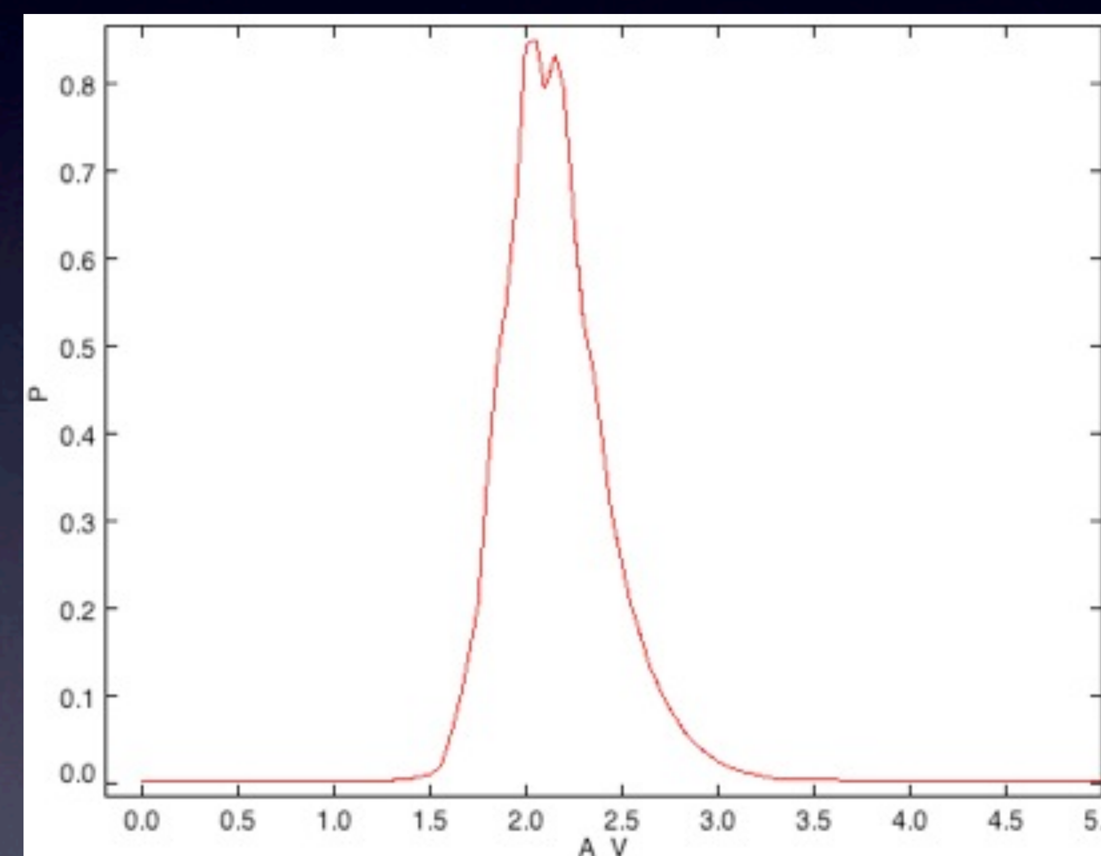
Dereddening

- In *i-Z*, *J-H* CCD degeneracy is broken due to water opacity
- Effects of discs minimised
- Reddening vector perpendicular to sequence



A Bayesian Approach





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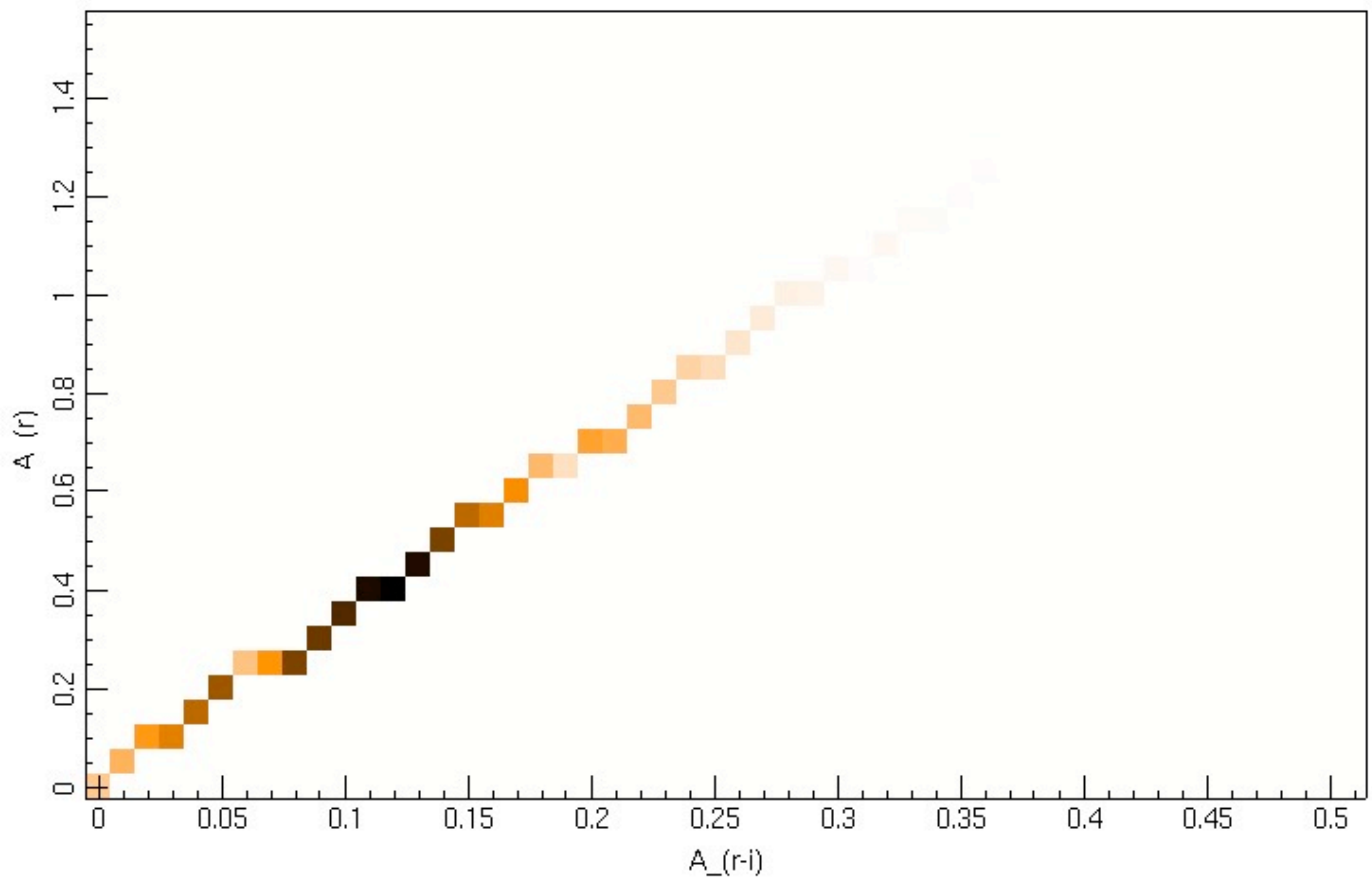

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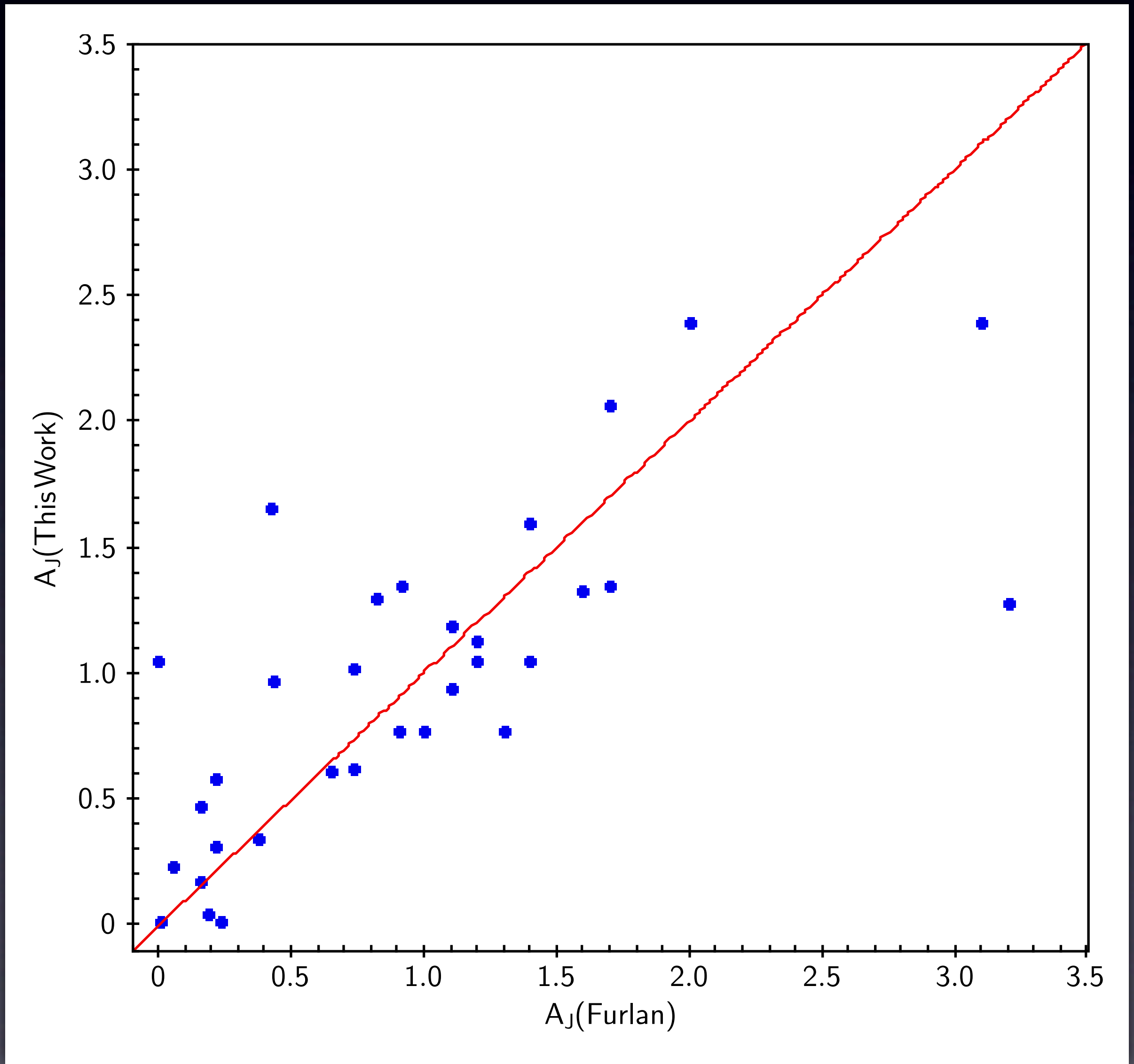
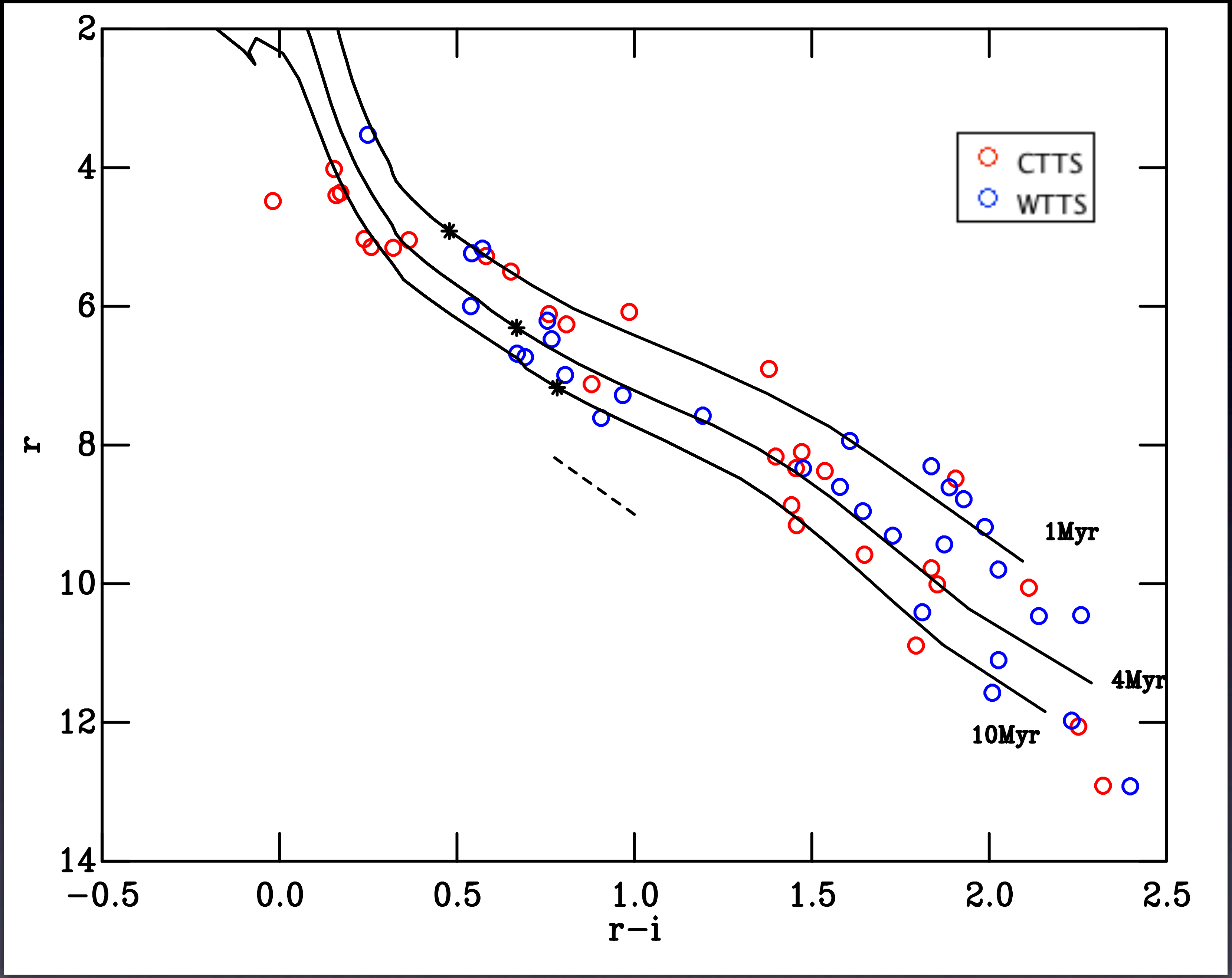
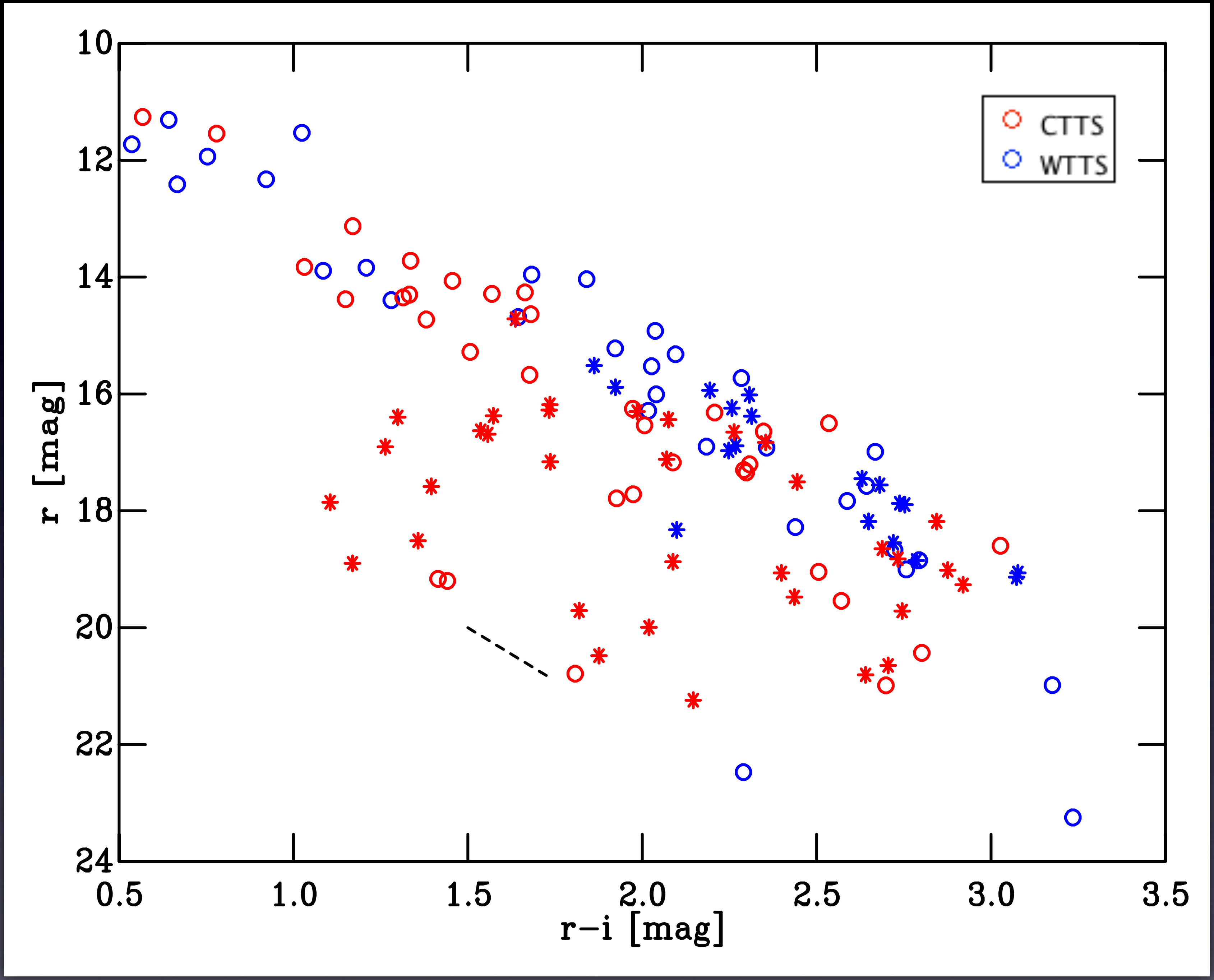
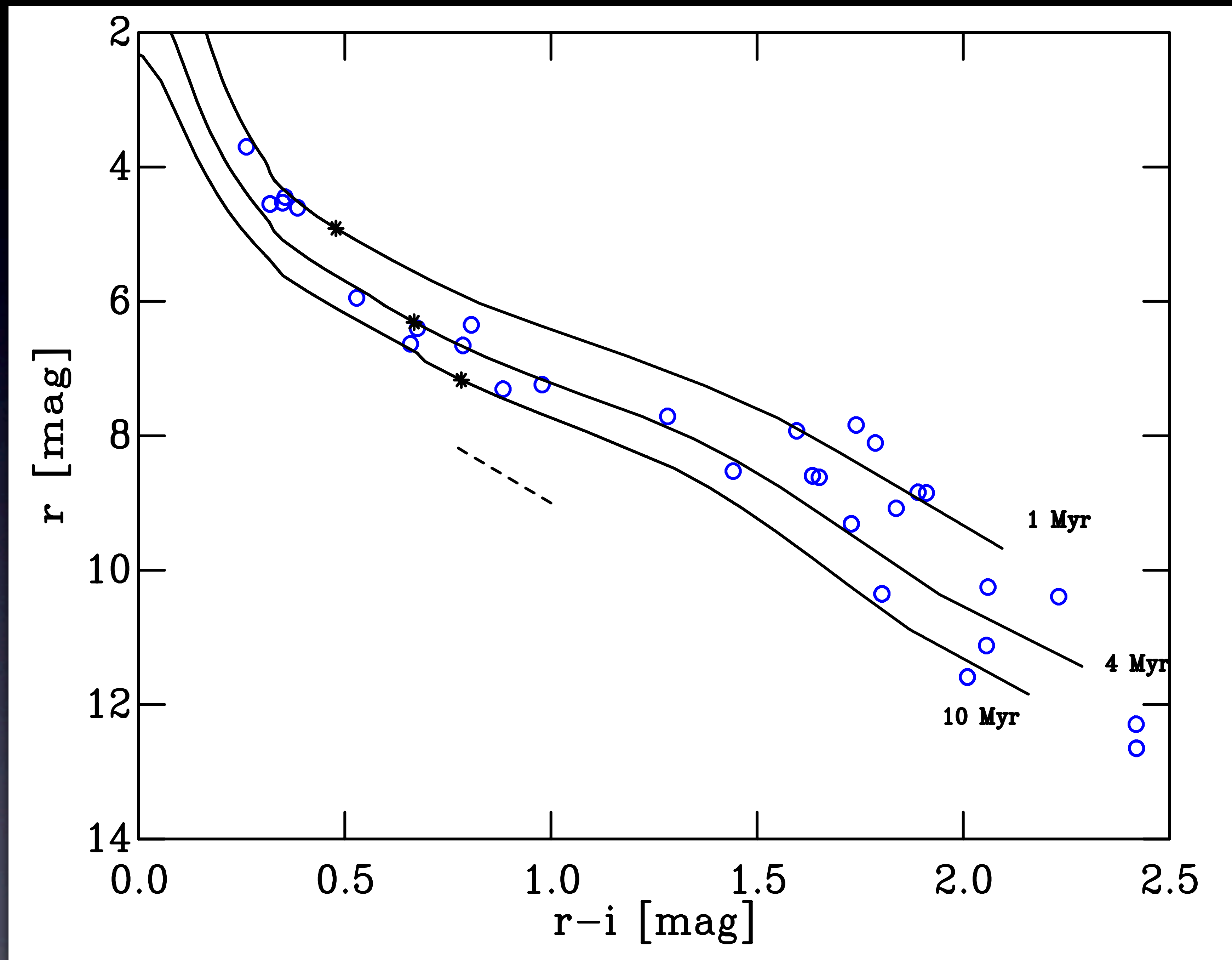


Age of Taurus





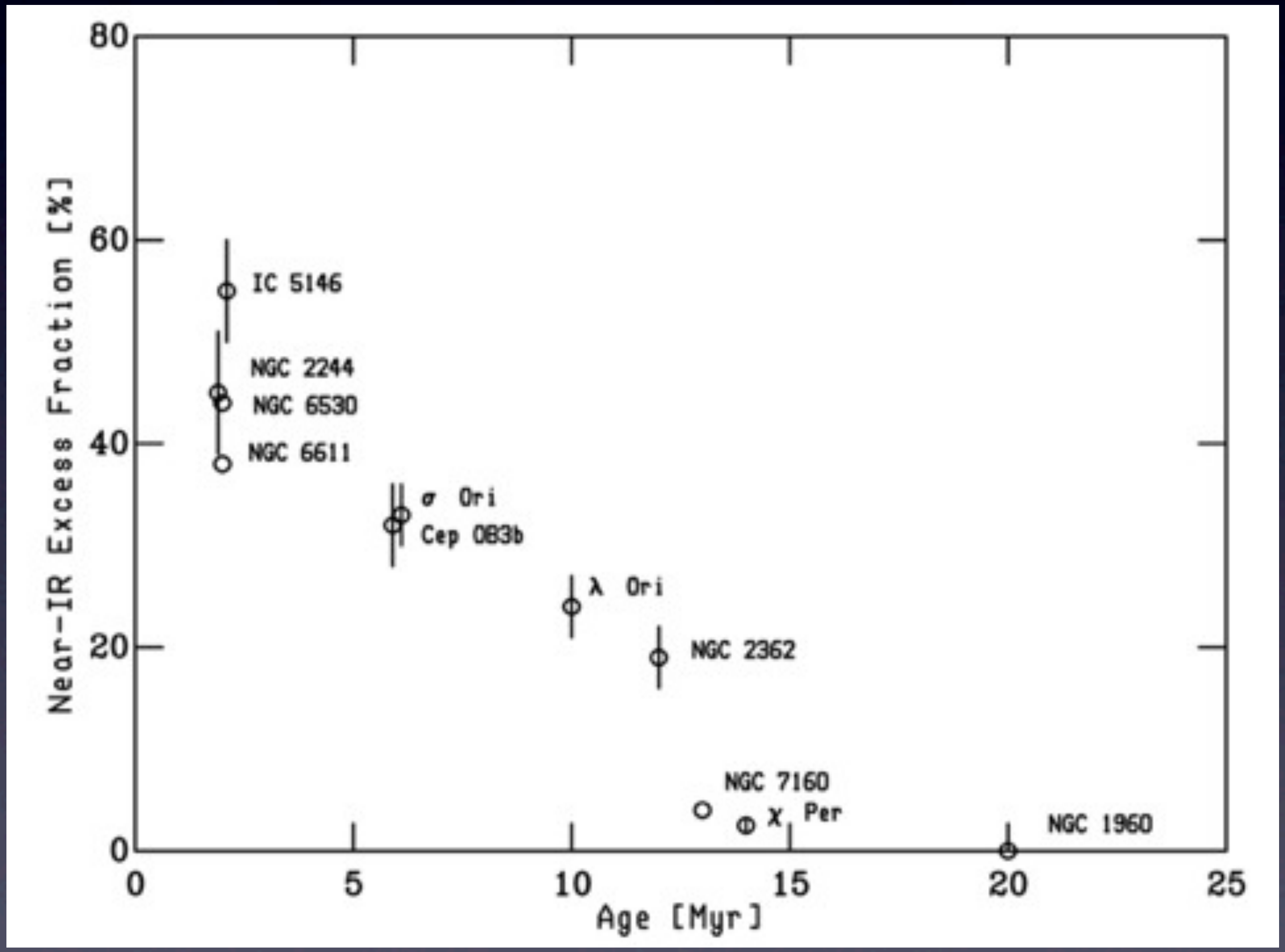
CTTS
WTTS
r [mag]
r−i [mag]
10
12
14
16
18
20
22
24
0.5
1.0
1.5
2.0
2.5
3.0
3.5



r [mag]
r−i [mag]
1 Myr
4 Myr
10 Myr

- Upper sequence - fit classics AND weaks (3 million yrs)
  - Advantage: consistent with Bell et al. clusters
  - Disadvantage: short sequence to fit
- Or fit whole sequence (weaks only) - (3 million years)
  - Advantage: long sequence to fit
  - Disadvantage: does weaks only bias us?
- But both give same answer!

Implications - Disc Fraction



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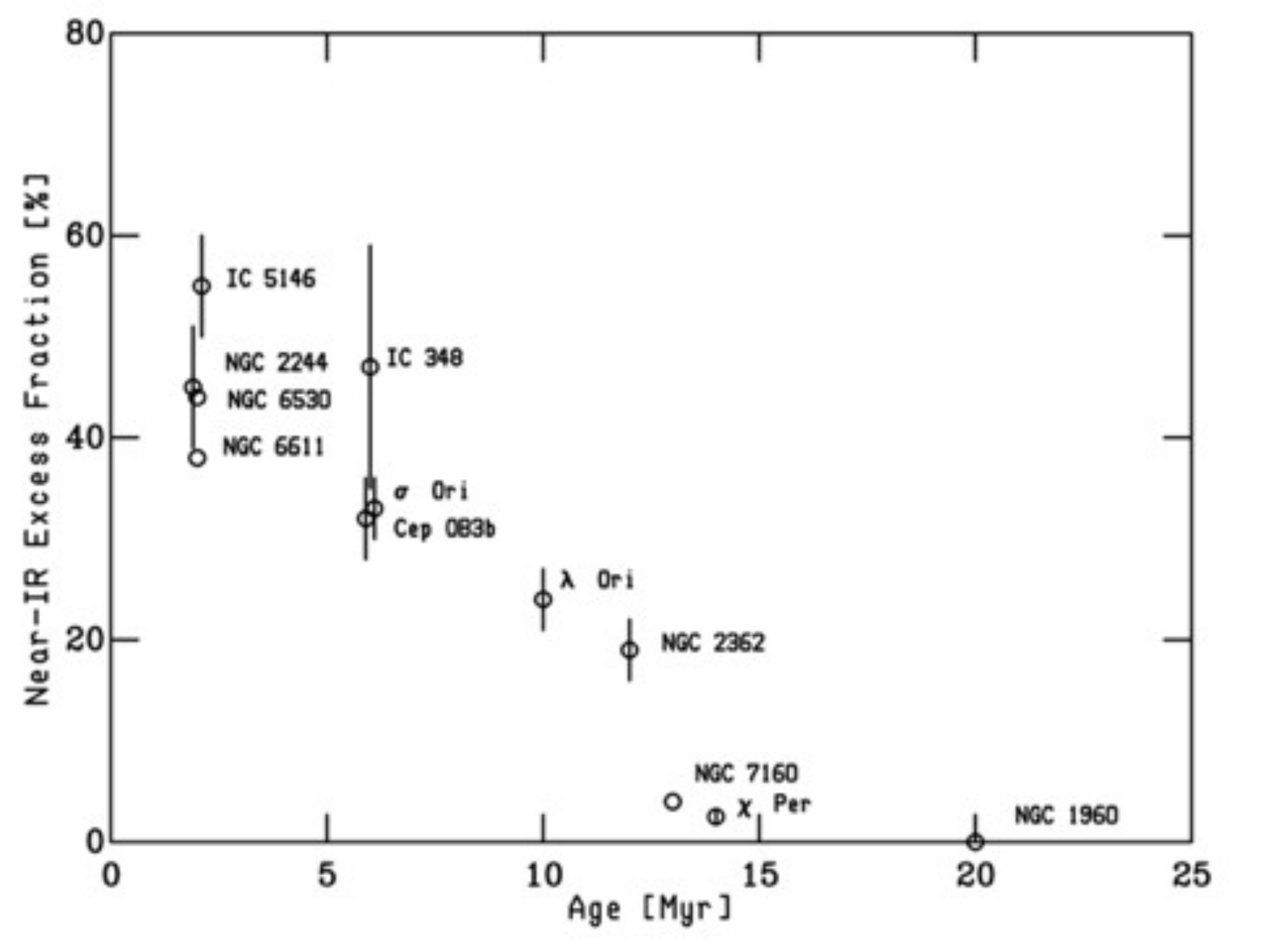

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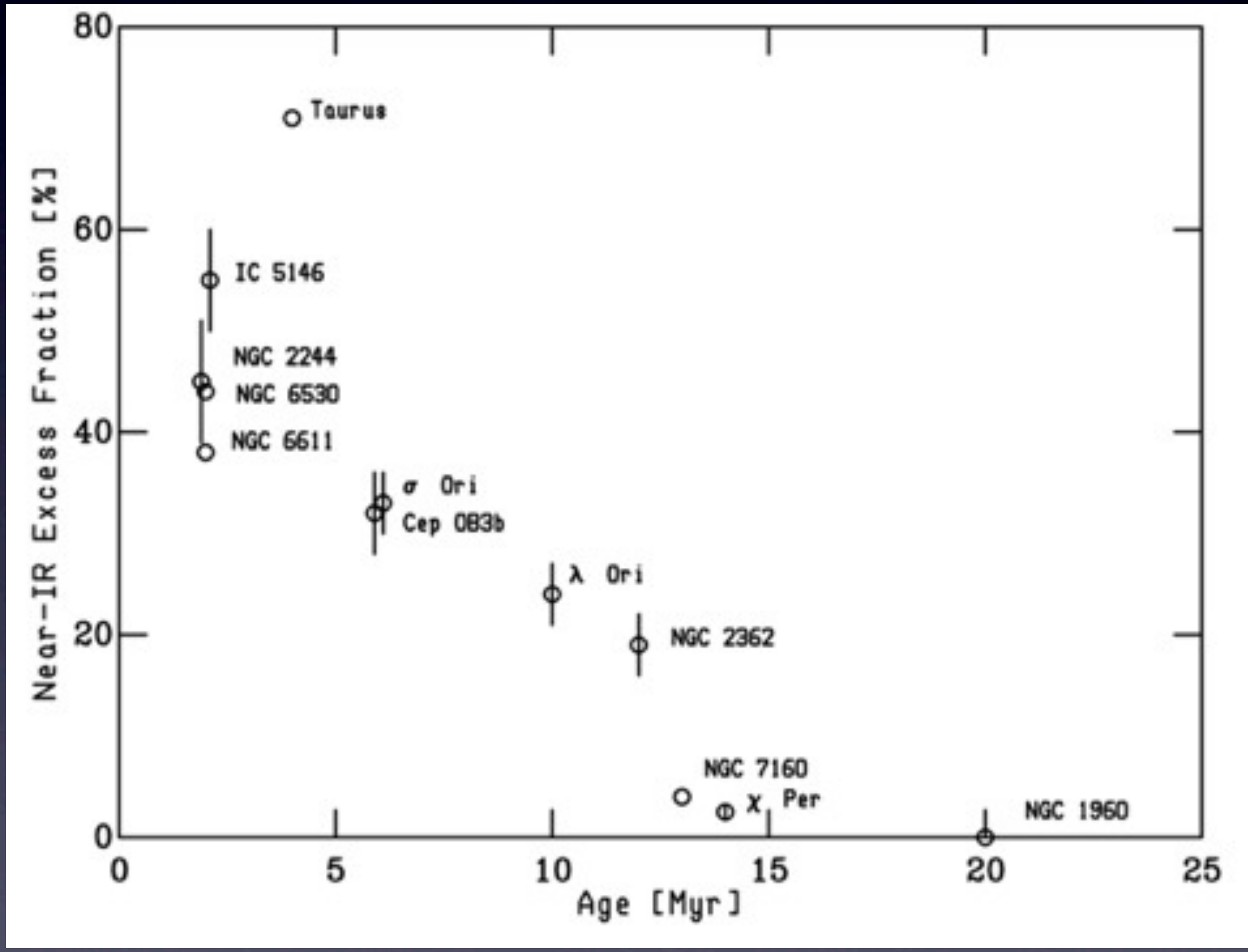

Conclusions

- Using a Bayesian method we can derive robust, consistent extinctions from photometry
- Taurus older than commonly quoted (3-4Myr)
- Consequently, it appears disks may survive longer in low density region

Conclusions

- We have brought the MS and PMS age scales into agreement.
- Revised age scale is factor two longer than canonical scale.
- Consequences so far look “helpful”.
- First signs of environment affecting disc dissipation.
- Few more well-known young regions to do.
- Isochrones now available in various photometric systems - http://www.astro.ex.ac.uk/people/timn/isochrones/ - use them, they are the only isochrones which fit the low-mass data!
- Consistent masses, now we can derive mass functions.
- Why is there a MS/pre-MS age discrepancy for youngest objects?